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ICT Development and Sustainable Development in Nigeria: An ARDL Assessment of Economic, Social, and Environmental Dimensions

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Abstract

This study examines the effect of Information and Communication Technology (ICT) on sustainable development in Nigeria, focusing on its economic, social and environmental dimensions. Annual time-series data covering 1995–2024 were obtained from the World Development Indicators, United Nations Development Programme and International Telecommunication Union. Economic sustainability is proxied by GDP per capita growth, social sustainability by the Human Development Index, and environmental sustainability by carbon dioxide emissions. The study employs the Autoregressive Distributed Lag (ARDL) approach to estimate the short-run and long-run relationships. The findings reveal that ICT has a positive and statistically significant effect on economic sustainability in both the short and long run. ICT also exerts a positive and significant influence on social sustainability, indicating that greater ICT penetration is associated with improvements in human development. In contrast, ICT has a negative and statistically significant effect on carbon dioxide emissions in both periods, suggesting that ICT development does not contributes to improved environmental sustainability. The findings establish that ICT has heterogeneous but consistently significant effects across the three dimensions of sustainable development in Nigeria. The study concludes that expanding digital infrastructure, strengthening digital inclusion and promoting ICT-enabled green technologies are important for aligning Nigeria's digital transformation with sustainable development objectives.

Keywords: Information and Communication Technology; sustainable development; economic sustainability; social sustainability; environmental sustainability; Nigeria.

1. INTRODUCTION

Sustainable development remains a major policy challenge in Nigeria despite sustained government efforts to promote economic prosperity, social welfare and environmental protection. Following the adoption of the Sustainable Development Goals (SDGs) in 2015, initiatives such as the Economic Recovery and Growth Plan, National Digital Economy Policy and Strategy, National Development Plan (2021–2025) and Nigeria Agenda 2050 have sought to accelerate development. However, persistent poverty, unemployment, inadequate social services, infrastructural deficits and environmental degradation continue to constrain development outcomes. The National Bureau of Statistics (NBS, 2022) reported that about 38.9% of Nigerians, representing approximately 87 million people, lived below the national poverty line. Nigeria's low position in international sustainable development assessments further indicates that policy commitments have not translated sufficiently into broad-based and sustainable development.

Information and Communication Technology (ICT) has consequently attracted increasing attention as a potential instrument for addressing these development challenges. ICT can enhance productivity, innovation, financial access and economic efficiency by reducing information and transaction costs and expanding access to markets and services. Its contribution to economic sustainability, however, depends on the availability, affordability and effective use of digital infrastructure and skills (Horbach, 2024). Although internet access has expanded considerably in Nigeria, substantial disparities in connectivity and digital capabilities persist, particularly between urban and rural populations. These inequalities may limit the extent to which ICT generates

inclusive economic opportunities and sustained improvements in productivity and income (Bayar et al., 2024; Szalkowski & Johansen, 2024).

The relevance of ICT also extends to social sustainability. Digital technologies can improve access to education, healthcare, financial services and public information, thereby expanding opportunities for social participation. Nevertheless, unequal access to digital infrastructure and skills may reinforce existing socioeconomic inequalities. Rural and disadvantaged communities are particularly vulnerable to such exclusion, limiting their access to digital learning, telemedicine and technology-enabled financial and social services (Abbas & Zaman, 2024). Thus, ICT development may promote social inclusion only where digital access is sufficiently broad and affordable.

ICT also has important implications for environmental sustainability. Digital technologies can support energy efficiency, environmental monitoring, smart resource management and cleaner production, thereby improving the efficiency of resource utilisation (Khan et al., 2024; Gariba et al., 2024). However, inadequate digital infrastructure, limited technological integration into environmental governance and growing electronic waste may constrain these benefits. The environmental contribution of ICT in Nigeria therefore requires empirical assessment rather than being assumed to be inherently positive.

Although existing studies have established the relevance of ICT to various development outcomes, evidence on its simultaneous implications for the economic, social and environmental dimensions of sustainable development in Nigeria remains limited. This study addresses this gap by examining the effect of ICT development on sustainable development through these three dimensions. Specifically, the study seeks to: (i) examine the effect of ICT development on economic sustainability in Nigeria; (ii) assess the influence of ICT development on social sustainability in Nigeria; and (iii) evaluate the effect of ICT development on environmental sustainability in Nigeria. By addressing these objectives, the study provides empirical evidence that can assist policymakers in determining whether and through which dimensions ICT development contributes to sustainable development in Nigeria, thereby informing digital transformation strategies and policies directed towards more inclusive, resilient and environmentally sustainable development.

2. LITERATURE REVIEW

2.1 Conceptual Review

The concept of sustainable development emerged from growing concerns regarding the environmental consequences of economic growth during the 1960s and 1970s and gained global prominence through the report of the World Commission on Environment and Development, commonly known as the Brundtland Report, published in 1987. In that report, sustainable development was defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Subsequently, the concept has been expanded to incorporate economic prosperity, environmental integrity, and social inclusion as mutually reinforcing dimensions of development. Sustainable development has been described as a process through which economic advancement, environmental protection, and social welfare are simultaneously pursued to ensure long-term human well-being (Mensah, 2019; Purvis et al., 2019).

ICT has been described as an integrated system comprising computers, internet services, telecommunication devices, software applications, and digital platforms that facilitate

communication and information management across individuals, organizations, and societies (Vu et al., 2020). Similarly, ICT has been viewed as a technological infrastructure that supports knowledge creation, innovation, and connectivity through digital networks and communication tools (Adeleye et al., 2021). The economic dimension of sustainable development is significantly influenced by ICT through its effects on productivity, innovation, efficiency, and economic growth. ICT facilitates the automation of production processes, reduces transaction costs, improves market efficiency, and enhances access to financial services through digital platforms and electronic commerce (Myovella et al., 2020). In the social dimension of sustainable development, ICT contributes to improved access to education, healthcare, public services, and information resources through online learning, telemedicine, social networking, and e-governance initiatives, which strengthen social inclusion and human development outcomes (Adeleye et al., 2021) ICT supports environmental monitoring, resource optimization, energy efficiency, and the deployment of smart technologies that reduce waste and improve environmental management. (Charfeddine & Umlai, 2023). However, environmental concerns have also been linked to ICT expansion due to increasing energy consumption by data centres, communication networks, and digital devices, as well as the growing challenge of electronic waste disposal (Alojail & Khan, 2023).

2.2 Theoretical Review

The Endogenous Growth Theory was propounded by Paul Romer in 1986 as an alternative to the neoclassical growth framework, which attributed long-run economic growth primarily to exogenous technological progress. The theory was developed on the premise that economic growth is generated internally through deliberate investments in human capital, research and development, innovation, and knowledge accumulation. The relevance of the Endogenous Growth Theory to the present study is derived from its explanation of the mechanisms through which ICT contributes to sustainable development (Pradhan et al., 2023; Jones, 2019). ICT constitutes a critical form of technological capital that enhances knowledge creation, information dissemination, innovation, and productivity across sectors of the economy. Through investments in digital infrastructure, internet connectivity, telecommunications networks, and information systems, efficiency gains are realized, transaction costs are reduced, and access to productive opportunities is expanded.

The Diffusion of Innovation (DOI) Theory was propounded by Everett Rogers in 1962 and subsequently refined through several editions of his work, culminating in the fifth edition published in 2003. The theory was developed to explain the manner in which innovations are communicated and adopted within a social system over time. It was assumed that the adoption of an innovation is influenced by the perceived characteristics of the innovation, namely relative advantage, compatibility, complexity, trialability, and observability (Kapoor et al., 2024). The relevance of the Diffusion of Innovation Theory to the present study lies in its ability to explain how information and communication technologies are adopted and utilized to promote sustainable development. Sustainable development outcomes can only be realized when ICT innovations are successfully diffused across households, businesses, educational institutions, and government agencies through increased adoption of internet services, mobile technologies, digital platforms, and communication networks, access to information, education, healthcare, financial services, and productive opportunities (Buchanan et al., 2023).

2.3 Empirical Review

Vu, Hanafizadeh, and Bohlin (2020) assessed the contribution of ICT to economic growth using evidence from developing economies. Through panel data estimation techniques, ICT infrastructure was found to improve productivity and economic performance through enhanced information exchange and technological diffusion. Furthermore, Siddiqui and Singh (2020) analyzed the relationship between ICT penetration and economic growth in major trading nations from 2001 to 2018. Principal Component Analysis and panel regression techniques were employed to construct an ICT penetration index. The findings showed that ICT penetration significantly stimulated economic growth, trade openness, and foreign direct investment. Thereafter, Habibi and Zabardast (2021) examined the impact of ICT on economic growth across 120 countries between 2002 and 2017. A composite ICT index consisting of internet users, broadband subscriptions, and mobile subscriptions was constructed, and panel estimation techniques were applied. ICT was found to positively influence economic growth in both developed and developing countries, although greater gains were recorded among low-income economies. In the same year, Liu, Latif, Xiong, Yang, Latif, and Ul Wara (2021) investigated the nexus among globalization, ICT, and economic growth using panel data from developing economies. Generalized Method of Moments (GMM) estimation was employed, and ICT was found to contribute significantly to economic growth by facilitating integration into the global economy.

Similarly, Asongu and Odhiambo (2022) examined ICT and economic growth in Sub-Saharan Africa using panel data from 44 countries covering 2004–2020. Panel-Corrected Standard Errors and System GMM techniques were utilized. The findings revealed that ICT promoted economic growth directly and indirectly through education, investment, and trade openness. Using Nigerian data spanning 2000–2021, Ndam, Madaki, Uwondo, and Naanzem (2023) investigated the contribution of teledensity to economic growth through the ARDL bounds testing framework. The results established that telecommunications development exerted a positive and statistically significant impact on economic growth in both the short and long run. Likewise, Wainaina (2024) examined the impact of ICT on economic growth in Sub-Saharan African countries between 2000 and 2022. Fixed-effects panel estimation techniques were employed. Mobile penetration, internet usage, and broadband subscriptions were found to enhance economic growth significantly through improvements in productivity and financial inclusion.

Evidence from ICT-social sustainability reveals different findings. Asongu and Le Roux (2019) investigated the relationship between ICT, financial inclusion, and inequality reduction in African countries between 2004 and 2014. Using System GMM estimation, ICT adoption was found to reduce social exclusion by improving access to financial services among previously underserved populations. The study further established that mobile technologies contributed significantly to poverty reduction and social empowerment. Thereafter, García-Quismondo and Rios (2019) examined the contribution of digital technologies to educational development in Latin American countries. Panel regression techniques were employed using data spanning 2005–2017. The results indicated that internet access and digital learning tools significantly improved educational attainment and reduced disparities in access to knowledge resources. Using a global sample of countries from 2000 to 2018, Vu, Hanafizadeh, and Bohlin (2020) investigated the developmental implications of ICT adoption. Panel data methodologies were employed, and ICT infrastructure was found to improve social welfare through enhanced access to information, education, healthcare, and employment opportunities. The study concluded that digital inclusion constitutes an important determinant of sustainable social development. Furthermore, Alhassan and Adam

(2021) examined the effect of digital financial services on social inclusion in Sub-Saharan Africa using panel data from 42 countries covering 2011–2018. System GMM estimation was utilized. The findings showed that mobile money and digital financial technologies significantly improved financial inclusion and reduced social disparities among vulnerable populations. In another study, Kurniawati, Shanks, and Bekmamedova (2021) assessed the contribution of ICT-enabled public services to social development in developing countries. Survey data and structural equation modelling were employed. ICT-based public services were found to improve citizens' access to healthcare, education, and government services, thereby strengthening social sustainability outcomes. Similarly, Aker and Blumenstock (2022) investigated the role of mobile technologies in promoting social inclusion across developing economies. Using household-level survey data and econometric estimation techniques, mobile phone access was found to improve information dissemination, educational participation, and access to healthcare services. Using data from 125 countries between 2005 and 2020, Shahbaz, Awad, and Elgammal (2022) examined the influence of digitalization on human development. Panel cointegration and fully modified ordinary least squares estimation techniques were employed. The findings revealed that ICT significantly enhanced human development by improving literacy rates, healthcare outcomes, and labour market participation. Likewise, Andersson and Hatakka (2023) investigated the contribution of ICT to the achievement of social dimensions of the Sustainable Development Goals across developing countries. Through systematic empirical assessment and comparative analysis, ICT adoption was found to enhance social inclusion, educational access, and institutional responsiveness, thereby supporting sustainable social development. Furthermore, Alojail and Khan (2023) examined the implications of digital transformation for sustainable development across emerging economies. Panel estimation techniques were employed, and digital technologies were found to improve social welfare through increased accessibility to information, digital learning opportunities, and improved healthcare service delivery. Using panel data from developing economies between 2008 and 2022, Saba, Ngepah, and Odhiambo (2024) investigated the role of ICT in promoting development outcomes. Dynamic panel estimation techniques were employed, and ICT infrastructure was found to significantly improve social inclusion, poverty reduction, and access to public services.

Several studies were reviewed on the relationship between ICT and environmental sustainability. Using panel data from 58 countries spanning 1995–2017, Shahbaz, Khan, Ali, and Bhattacharya (2020) investigated the relationship between ICT and environmental sustainability. Dynamic panel estimation techniques were employed. ICT development was found to reduce carbon emissions through improvements in technological efficiency and innovation-driven environmental management. Furthermore, Khan, Baloch, Saud, and Fatima (2020) assessed the role of ICT in achieving environmental sustainability within developing economies. Panel cointegration and causality techniques were employed using data from 1990–2018. ICT was found to contribute positively to environmental quality through reductions in energy intensity and enhanced adoption of environmentally friendly technologies. Similarly, Park, Meng, and Baloch (2021) examined ICT, renewable energy consumption, and environmental sustainability across Asian economies. Panel ARDL and FMOLS techniques were utilized. The findings revealed that ICT significantly improved environmental sustainability by supporting renewable energy integration and reducing environmental pressures associated with industrial activities. Likewise, Yang, Ali, Hashmi, and Shabir (2021) examined the impact of digital technologies on environmental performance in Belt and Road Initiative countries. System GMM estimation was employed. The results established that ICT significantly improved environmental quality by promoting green innovation and sustainable

production practices. In another study, Chatti (2022) investigated the relationship between ICT development and ecological sustainability in developing countries between 1995 and 2020. Panel threshold estimation techniques were employed. ICT was found to exert a significant positive influence on environmental sustainability, particularly in countries with higher levels of institutional quality and technological readiness. Similarly, Alvarado, Tillaguango, Méndez, Bravo, and Chamba (2022) examined the effects of ICT and innovation on environmental sustainability in Latin American countries. Panel econometric techniques were employed using data covering 2000–2019. ICT development was found to reduce environmental degradation through improved technological efficiency and cleaner production systems.

3. METHODOLOGY

This study adopts an ex-post facto research design, which is appropriate for investigating relationships among macroeconomic variables using historical data over which the researcher has no direct control. The design is considered suitable because ICT development and sustainable development indicators are outcomes of past technological, institutional, economic, and environmental conditions.

This study is anchored on the Diffusion of Innovation Theory propounded by Rogers (1962). The theory explains how innovations and technologies spread through societies and influence economic and social outcomes over time. According to the theory, technological innovations are adopted through communication channels within a social system, resulting in improvements in productivity, information dissemination, efficiency, and welfare.

The theory posits that the developmental impact of technology depends on the extent to which innovations are diffused and adopted across sectors of the economy. As ICT infrastructure expands and digital technologies become widely accessible, improvements are expected in economic productivity, social inclusion, and environmental management.

Following the diffusion framework, sustainable development can be expressed as a function of ICT development and other complementary macroeconomic factors:

$$SD = f(ICT, GFCF, HC, URB) \quad 3.1$$

Where: SD = Sustainable Development; ICT = Information and Communication Technology Development; GFCF = Gross Fixed Capital Formation; HC = Human Capital Development; URB = Urbanization

Since sustainable development comprises economic, social, and environmental dimensions, the theoretical relationship may be decomposed as:

$$ES = f(ICT, GFCF, HC, URB) \quad 3.2$$

$$SS = f(ICT, GFCF, HC, URB) \quad 3.3$$

$$ENS = f(ICT, GFCF, HC, URB) \quad 3.4$$

Where: ES = Economic Sustainability; SS = Social Sustainability; ENS = Environmental Sustainability

The empirical model is adapted from the ICT-development framework employed by Myovella et al. (2020), Alojail and Khan (2023), and Saba et al. (2024), which examined the developmental effects of ICT across countries.

The baseline functional model is specified as:

$$SD = f(ICT, GFCF, HC, URB) \quad 3.5$$

To achieve the specific objectives of the study, three separate models are estimated.

Model I: ICT and Economic Sustainability

Economic sustainability is proxied by GDP per capita growth (GDPG).

$$GDPG = f(ICT, GFCF, HC, TRD) \quad 3.6$$

The econometric model is specified as:

$$GDPG_t = \delta_0 + \delta_1 ICT_t + \delta_2 GFCF_t + \delta_3 HC_t + \delta_4 TRD_t + \varepsilon_t \quad 3.7$$

Model II: ICT and Social Sustainability

Social sustainability is proxied by the Human Development Index (HDI).

$$HDI = f(ICT, GFCF, HC, TRD) \quad 3.8$$

The econometric model is specified as:

$$HDI_t = \delta_0 + \delta_1 ICT_t + \delta_2 GFCF_t + \delta_3 HC_t + \delta_4 TRD_t + \varepsilon_t \quad 3.9$$

Model III: ICT and Environmental Sustainability

Environmental sustainability is proxied by CO_2 emissions per capita (CO2).

$$CO_2 = f(ICT, GFCF, HC, TRD) \quad 3.10$$

The econometric model is specified as:

$$CO2_t = \delta_0 + \delta_1 ICT_t + \delta_2 GFCF_t + \delta_3 HC_t + \delta_4 TRD_t + \varepsilon_t \quad 3.11$$

The short-run ARDL model with error correction can be written as:

$$\Delta Y_t = \alpha_0 + \sum_{i=1}^{k} \beta_1 \Delta ICT_{t-1} + \sum_{i=1}^{k} \beta_2 \Delta GFCF_{t-1} + \sum_{i=1}^{k} \beta_3 \Delta HC_{t-1} + \sum_{i=1}^{k} \beta_5 \Delta URB_{t-1} + \lambda_1 ECT_{t-1} + \varepsilon_t \quad 3.12$$

Where (Y) represents GDPG, HDI, and CO_2 respectively.

3.4 *A Priori* Expectations

Table 3.1 presents expected signs of the explanatory variables based on Diffusion of Innovation Theory and the empirical literature on ICT and sustainable development.

Table 3.1: *A Priori* Expectations

Variable	Economic Sustainability (GDPG)	Social Sustainability (HDI)	Environmental Sustainability (CO_2)	Supporting Studies
ICT	Positive	Positive	Negative	Myovella et al. (2020); Charfeddine & Umlai (2023)
GFCF	Positive	Positive	Positive	Alojail & Khan (2023)
HC	Positive	Positive	Negative	Saba et al. (2024)
TRD	Positive	Positive	Positive	Shahbaz et al. (2020)

Source: Author's Computation (2026)

The variables utilized in this study are measured using internationally recognized indicators. Annual secondary data covering the period 1995–2024 are obtained from the World Development Indicators (WDI), United Nations Development Programme (UNDP), and International Telecommunication Union (ITU). The measurement of the variables are presented in Table 3.2

Table 3.2: Measurement of Variables

Variable	Measurement	Source
Economic Sustainability (GDPG)	GDP per capita growth (annual %)	WDI (2025)
Social Sustainability (HDI)	Human Development Index	UNDP (2025)
Environmental Sustainability (CO_2)	CO_2 emissions (metric tons per capita)	WDI (2025)
ICT Development (ICT)	Individuals using the internet (% of population)	ITU/WDI (2025)
Gross Fixed Capital Formation (GFCF)	Gross fixed capital formation (% GDP)	WDI (2025)
Human Capital (HC)	Secondary school enrolment (%)	WDI (2025)
Trade (TRD)	Trade (% of GDP)	WDI (2025)

Source: Author's Computation (2026)

The analysis commences with descriptive statistics to examine the distributional characteristics and behaviour of the variables over the study period. Thereafter, correlation analysis is conducted to determine the degree of association among the variables. The stationarity properties of the variables are examined using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests. These tests are employed to ascertain the order of integration of the variables and to avoid spurious regression results.

Following the unit root tests, the Autoregressive Distributed Lag (ARDL) bounds testing approach developed by Pesaran, Shin, and Smith (2001) is employed to determine the existence of long-run relationships among the variables. The ARDL technique is considered appropriate because it

accommodates variables integrated at I(0) and I(1), performs efficiently with relatively small sample sizes, and simultaneously estimates both short-run dynamics and long-run equilibrium relationships within a unified framework. Where cointegration is established, the Error Correction Model (ECM) is estimated to capture the speed at which short-run disequilibrium adjusts to the long-run equilibrium path. Diagnostic tests including serial correlation, heteroskedasticity, normality, and model stability tests (CUSUM and CUSUMSQ) are further conducted to ensure the robustness and reliability of the estimated models.

4. RESULTS AND DISCUSSION

4.1 Pre-Estimation Tests

Table 4.1: Descriptive Statistics

	GDPG	HDI	CO2	ICT	GFCF	HC	TRD
Mean	4.3308	0.4939	0.6604	14.4974	13.1187	36.0377	46.3733
Median	4.2744	0.5005	0.6216	10.4000	11.8120	38.2225	44.0000
Maximum	15.3292	0.5650	0.9110	41.2114	21.0590	52.7967	64.8000
Minimum	-6.3689	0.4020	0.4993	0.0080	10.6896	22.0324	31.4000
Std. Dev.	3.8891	0.0502	0.1071	14.2050	3.0878	9.0596	10.6315
Skewness	-0.0263	-0.4107	0.7021	0.5195	1.4858	-0.2081	0.2581
Kurtosis	4.8469	1.9502	2.3999	1.8841	3.7674	1.8434	1.6580
Jarque-Bera	4.2672	2.2209	2.9146	2.9060	11.7744	1.8886	2.5846
Probability	0.1184	0.3294	0.2329	0.2339	0.0028	0.3889	0.2746
Observations	30	30	30	30	30	30	30

Note: GDPG denotes GDP per Capita Growth; HDI represents Human Development Index; CO_2 denotes Carbon Dioxide Emissions; ICT represents Information and Communication Technology; GFCF denotes Gross Fixed Capital Formation; HC represents Human Capital; TRD denotes Trade Openness.
Source: Author's Computation (2026).

Table 4.1 presents the descriptive statistics of the variables employed in the analysis covering the period 1995–2024. GDP per capita growth (GDPG) recorded an average growth rate of 4.33%, with values ranging from –6.37% to 15.33%, indicating considerable fluctuations in Nigeria's economic performance during the study period.

The Human Development Index (HDI) recorded an average value of 0.494, suggesting a moderate level of human development. The minimum and maximum values of 0.402 and 0.565 indicate gradual improvements in welfare outcomes over time. Carbon dioxide emissions (CO_2) recorded a mean value of 0.660 tonnes per capita, with relatively small dispersion, indicating moderate environmental pressure.

Information and Communication Technology (ICT) recorded an average value of 14.50%, while the maximum value of 41.21% reflects the rapid expansion of ICT penetration in recent years. Gross Fixed Capital Formation (GFCF) averaged 13.12% of GDP, indicating a moderate level of investment activity throughout the study period.

Human Capital (HC) recorded a mean value of 36.04 years, suggesting gradual improvement in educational attainment. Trade openness (TRD) recorded an average value of 46.37% of GDP, reflecting the considerable role of international trade in the Nigerian economy.

The Jarque-Bera probabilities indicate that all variables, except GFCF, are normally distributed at the 5% significance level since their probability values exceed 0.05. Although GFCF departs from normality, this does not invalidate the subsequent econometric analysis because the ARDL methodology is robust to moderate departures from normality.

Table 4.2: Correlation Matrix

Variables	GDPG	HDI	CO2	ICT	GFCF	HC	TRD
GDPG	1.0000						
HDI	-0.2109	1.0000					
CO2	0.0979	-0.7482	1.0000				
ICT	-0.4192	0.7151	-0.6921	1.0000			
GFCF	-0.3414	0.6072	-0.4306	0.7133	1.0000		
HC	-0.1106	0.7251	-0.7787	0.7345	0.4605	1.0000	
TRD	0.6854	-0.3895	0.1394	-0.6740	-0.4778	-0.3377	1.0000

Source: Author's Computation (2026).

Table 4.2 presents the pairwise correlation coefficients among the study variables. GDP per capita growth exhibits a moderate positive relationship with trade openness (0.6854), implying that greater openness to international trade is associated with higher economic growth. Conversely, GDP per capita growth is negatively associated with ICT (–0.4192), gross fixed capital formation (–0.3414), human development (–0.2109), and human capital (–0.1106), while only a weak positive relationship is observed with carbon dioxide emissions (0.0979).

Among the explanatory variables, ICT exhibits strong positive correlations with human capital (0.7345), gross fixed capital formation (0.7133), and human development (0.7151). Carbon dioxide emissions display strong negative relationships with human capital (–0.7787), human development (–0.7482), and ICT (–0.6921). Trade openness is negatively related to ICT, gross fixed capital formation, human capital, and human development.

The highest correlation coefficient among the explanatory variables is 0.7787, which remains below the conventional threshold of 0.80. Consequently, the correlation analysis suggests that severe multicollinearity is absent among the regressors, indicating that the explanatory variables are suitable for subsequent econometric estimation.

Table 4.3: Augmented Dickey-Fuller (ADF) Unit Root Test

Variable	Level	First Difference	Order of Integration
GDPG	-3.0307**	–	I(0)
HDI	–	-3.2647**	I(1)
CO_2	-3.0967**	–	I(0)
ICT	–	-5.5338***	I(1)
GFCF	–	-3.8887***	I(1)
HC	–	-6.2999***	I(1)
TRD	–	-4.3824***	I(1)

Key: ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.
Source: Author's Computation (2026).

The Augmented Dickey-Fuller unit root test results reported in Table 4.3 indicate that the variables exhibit mixed orders of integration. GDP per capita growth (GDPG) and carbon dioxide emissions (CO_2) are stationary at levels, implying that they are integrated of order zero, I(0). In contrast, Human Development Index (HDI), Information and Communication Technology (ICT), Gross Fixed Capital Formation (GFCF), Human Capital (HC), and Trade Openness (TRD) become stationary after first differencing, indicating integration of order one, I(1).

The presence of both I(0) and I(1) variables confirms that none of the variables is integrated of order two, I(2). Consequently, the use of the Autoregressive Distributed Lag (ARDL) estimation technique is considered appropriate because it accommodates variables with mixed integration orders while simultaneously estimating both the short-run dynamics and the long-run equilibrium relationships.

Table 4.4: Johansen Cointegration Test (Trace Statistic)

Hypothesized No. of CE(s)	Trace Statistic	5% Critical Value	Probability
None*	126.4897	69.8189	0.0000
At most 1*	73.6250	47.8561	0.0000
At most 2*	33.0278	29.7971	0.0205
At most 3	13.1000	15.4947	0.1112
At most 4*	4.8003	3.8415	0.0284

Note: * indicates rejection of the null hypothesis at the 5% significance level.
Source: Author's Computation (2026).

The Johansen Trace Cointegration Test results presented in Table 4.4 reveal the existence of three cointegrating equations at the 5% significance level. The trace statistics for the hypotheses of none, at most one, and at most two exceed their corresponding critical values, resulting in the rejection of the null hypotheses of no cointegration. Although the trace statistic for the hypothesis of at most

four also exceeds its critical value, the Johansen trace summary indicates the existence of three cointegrating vectors, which forms the basis for interpretation.

The findings confirm the existence of a stable long-run equilibrium relationship among GDP per capita growth, information and communication technology, gross fixed capital formation, human capital, and trade openness in Nigeria. This implies that although short-run deviations may occur, the variables tend to move together over time and converge towards their long-run equilibrium path. The confirmation of cointegration therefore provides sufficient justification for estimating the ARDL long-run and error correction models.

4.2 Regression Results

4.2.1 Analysis of the Effect of ICT on Economic Sustainability in Nigeria

Table 4.5: ARDL Result

Dependent Variable: Economic Sustainability (GDPG)		
Variables	**Short-Run Coefficient**	**Long-Run Coefficient**
ICT	6.2371*** (2.7919)	5.1816** (2.7733)
GFCF	-2.7181 (-0.8446)	-2.2581 (-0.8905)
HC	7.1542** (2.3957)	5.9436** (2.7107)
TRD	11.0140*** (3.1683)	9.1502*** (3.9434)
ECM(-1)	-1.2037*** (-5.0512)	—

Key: ***, ** and * denote significance at the 1%, 5% and 10% levels respectively. Figures in parentheses are t-statistics.
Note: GDPG = GDP per Capita Growth (Economic Sustainability); ICT = Information and Communication Technology; GFCF = Gross Fixed Capital Formation; HC = Human Capital; TRD = Trade Openness.
Source: Author's Computation (2026).

The ARDL estimates reported in Table 4.5 indicate that Information and Communication Technology (ICT) exerts a positive and statistically significant effect on economic sustainability in both the short run and the long run. In the short run, the coefficient of ICT is 6.237, implying that a 1% increase in ICT penetration increases GDP per capita growth by approximately 6.24%, holding other variables constant. The result is statistically significant at the 5% level, suggesting that improvements in digital infrastructure and ICT adoption stimulate economic activities through enhanced productivity, innovation, and efficiency.

Similarly, ICT maintains a positive and significant long-run coefficient of 5.182, indicating that sustained expansion in ICT contributes significantly to long-term economic sustainability in Nigeria. The finding suggests that continuous investment in digital technologies strengthens productive capacity, promotes technological innovation, and enhances economic competitiveness.

Gross Fixed Capital Formation (GFCF) exhibits a negative coefficient in both the short run (-2.718) and the long run (-2.258), although both coefficients are statistically insignificant. The

result implies that physical capital accumulation has not exerted a significant influence on economic sustainability during the study period. This outcome may reflect the relatively low productivity of investment expenditure or inefficiencies associated with capital allocation.

Human Capital (HC) records a positive and statistically significant coefficient of 7.154 in the short run, indicating that improvements in educational attainment and skills development enhance economic sustainability by approximately 7.15%. The long-run coefficient of 5.944 further confirms that sustained investments in human capital significantly promote long-term economic growth through improvements in labour productivity and innovation.

Trade openness (TRD) also exerts a positive and statistically significant influence on economic sustainability. The short-run coefficient of 11.014 implies that increased international trade immediately stimulates economic growth through greater market access, technology transfer, and resource allocation efficiency. In the long run, the coefficient of 9.150 suggests that sustained integration into international markets contributes substantially to Nigeria's long-term economic sustainability.

The error correction term, ECM(-1), is negative and highly significant with a coefficient of -1.204. This satisfies the theoretical expectation of a negative adjustment coefficient and confirms the existence of a stable long-run equilibrium relationship among the variables. The coefficient indicates that approximately 120.4% of any short-run disequilibrium is corrected within one period. The adjustment speed, which exceeds unity, suggests an overshooting adjustment process whereby deviations from long-run equilibrium are corrected rapidly before converging to the equilibrium path.

Table 4.6: Post-Estimation Diagnostic Tests for Economic Sustainability Model

Test Statistics	Test Type	Value	Probability
Wald Test	F-statistic	5.4955	0.0290
Normality Test	Jarque-Bera	4.6960	0.0955
Serial Correlation	Breusch-Godfrey LM (F-statistic)	0.1354	0.8742
Heteroskedasticity	Breusch-Pagan-Godfrey (F-statistic)	2.2114	0.0825

Source: Author's Computation (2026).

From Table 4.6, the Wald test produces an F-statistic of 5.496 with a probability value of 0.029, indicating that the explanatory variables are jointly significant in explaining variations in economic sustainability. Consequently, the null hypothesis of joint insignificance is rejected at the 5% significance level. The Jarque-Bera statistic of 4.696 with a probability of 0.0955 indicates that the residuals are normally distributed since the probability exceeds the 5% significance level. Likewise, the Breusch-Godfrey LM test produces a probability value of 0.8742, suggesting the absence of serial correlation among the residuals. The Breusch-Pagan-Godfrey heteroskedasticity test records a probability value of 0.0825, implying that the null hypothesis of homoskedasticity cannot be rejected. Therefore, the residual variance is constant across observations.

4.2.2 Analysis of the Effect of ICT on Social Sustainability in Nigeria

Table 4.7: ARDL Result

Dependent Variable: Social Sustainability (HDI)		
Variables	**Short-Run Coefficient**	**Long-Run Coefficient**
ICT	0.0067*** (3.0271)	0.0113*** (4.8751)
GFCF	0.0070** (2.1239)	0.0274** (2.6827)
HC	0.0123** (2.3101)	0.0481* (2.0181)
TRD	0.0080 (1.6107)	-0.0357*** (-3.7140)
ECM(-1)	-0.2557** (-2.7165)	—

Key: ***, ** and * denote significance at the 1%, 5% and 10% levels respectively. Figures in parentheses are t-statistics.
Note: HDI = Human Development Index (Social Sustainability); ICT = Information and Communication Technology; GFCF = Gross Fixed Capital Formation; HC = Human Capital; TRD = Trade Openness.
Source: Author's Computation (2026).

The results presented in Table 4.7 reveal that ICT exerts a positive and statistically significant influence on social sustainability in both the short run and the long run. The short-run coefficient of 0.0067 indicates that a 1% increase in ICT penetration improves the Human Development Index by approximately 0.007 points. This finding suggests that increased digital connectivity improves access to education, healthcare, financial services, and information dissemination, thereby enhancing social welfare.

In the long run, ICT maintains a positive coefficient of 0.0113 and remains highly significant at the 1% level. The result demonstrates that sustained ICT development contributes positively to long-term improvements in human development through enhanced knowledge acquisition, innovation, and access to essential public services.

Gross Fixed Capital Formation records positive and statistically significant coefficients in both the short run (0.0070) and long run (0.0274), indicating that investment in physical infrastructure contributes positively to improvements in social sustainability.

Human Capital also exhibits positive and statistically significant effects. The short-run coefficient of 0.0123 indicates that improvements in educational attainment immediately enhance human development, while the long-run coefficient of 0.0481 confirms that sustained investment in education significantly improves social sustainability over time.

Trade openness displays a positive but statistically insignificant effect in the short run. However, the long-run coefficient is negative (-0.0357) and statistically significant, suggesting that increased openness may adversely affect human development in the long term if the gains from international trade are unevenly distributed or if domestic industries fail to benefit adequately from globalization.

The error correction coefficient, ECM(-1), is negative and statistically significant with a coefficient of -0.256, indicating that approximately 25.6% of short-run deviations from long-run equilibrium are corrected within one period. The result confirms the existence of a stable long-run equilibrium relationship among the variables.

Table 4.8: Post-Estimation Diagnostic Tests for Social Sustainability Model

Test Statistics	Test Type	Value	Probability
Wald Test	F-statistic	32.5928	0.0000
Normality Test	Jarque-Bera	0.9357	0.6263
Serial Correlation	Breusch-Godfrey LM (F-statistic)	0.5044	0.6127
Heteroskedasticity	Breusch-Pagan-Godfrey (F-statistic)	0.6984	0.6891
Functional Form	Ramsey RESET (F-statistic)	0.0004	0.9852

Source: Author's Computation (2026).

From Table 4.8, the Wald test reports an F-statistic of 32.593 with a probability value of 0.0000, indicating that the explanatory variables jointly exert a statistically significant influence on social sustainability. The Jarque-Bera probability value of 0.6263 confirms that the residuals are normally distributed. Likewise, the Breusch-Godfrey LM test produces a probability value of 0.6127, indicating that serial correlation is absent.

The Breusch-Pagan-Godfrey heteroskedasticity test reports a probability value of 0.6891, suggesting that the residuals exhibit constant variance. Furthermore, the Ramsey RESET test produces a probability value of 0.9852, indicating that the null hypothesis of correct model specification cannot be rejected. Hence, no evidence of functional form misspecification is observed.

4.2.3 Analysis of the Effect of ICT on Environmental Sustainability in Nigeria

Table 4.9: ARDL Result

Dependent Variable: Environmental Sustainability (CO_2)		
Variables	**Short-Run Coefficient**	**Long-Run Coefficient**
ICT	-0.0503*** (-4.4731)	-0.1092*** (-3.2017)
GFCF	0.1195 (1.5014)	-0.0688 (-0.7112)
HC	0.2684** (2.4465)	0.9484** (2.3052)
TRD	0.2756*** (3.5732)	0.0324 (0.3887)
ECM(-1)	-0.4606*** (-3.0737)	—

Key: ***, ** and * denote significance at the 1%, 5% and 10% levels respectively. Figures in parentheses are t-statistics.

Note: CO_2 = Carbon Dioxide Emissions (Environmental Sustainability); ICT = Information and Communication Technology; GFCF = Gross Fixed Capital Formation; HC = Human Capital; TRD = Trade Openness.
Source: Author's Computation (2026).

Table 4.9 presents the ARDL estimates of the effect of Information and Communication Technology (ICT) on environmental sustainability in Nigeria. The results reveal that ICT exerts a negative and statistically significant effect on CO_2 emissions in both the short run and the long run. Specifically, the short-run coefficient of –0.050 indicates that a 1% increase in ICT penetration reduces carbon dioxide emissions by approximately 0.05%, implying an immediate improvement in environmental sustainability. This finding suggests that ICT facilitates energy efficiency, digitalization of production processes, and improved environmental monitoring, thereby reducing environmental degradation.

Similarly, the long-run coefficient of –0.109 is negative and statistically significant at the 1% level, indicating that sustained investment in ICT reduces carbon emissions by approximately 0.11% in the long run. The result demonstrates that continuous technological advancement promotes cleaner production techniques, enhances energy efficiency, and supports environmental conservation.

Gross Fixed Capital Formation (GFCF) records a positive but statistically insignificant coefficient in the short run and a negative but insignificant coefficient in the long run. The findings imply that capital formation has not exerted a statistically meaningful influence on environmental sustainability during the study period. This outcome may reflect the dominance of conventional investment projects that are not sufficiently environmentally friendly.

Human Capital (HC) exhibits positive and statistically significant coefficients in both the short run (0.268) and the long run (0.948). Since the dependent variable is carbon emissions, the result suggests that improvements in human capital have been associated with increased economic activities and energy consumption, which consequently raise carbon emissions. This finding may reflect the expansion of productive activities accompanying improvements in education and labour productivity without corresponding adoption of cleaner technologies.

Trade openness (TRD) exerts a positive and statistically significant coefficient of 0.276 in the short run, indicating that increased international trade contributes to higher carbon emissions in the short term through increased production and transportation activities. However, the long-run coefficient is positive but statistically insignificant, suggesting that the long-term environmental effect of trade openness is relatively weak after controlling for other variables.

The error correction term, ECM(-1), records the expected negative and statistically significant coefficient of –0.461. This indicates that approximately 46.1% of short-run disequilibrium in environmental sustainability is corrected within one year. The magnitude and significance of the adjustment coefficient confirm the existence of a stable long-run equilibrium relationship among ICT, gross fixed capital formation, human capital, trade openness, and environmental sustainability.

Table 4.10: Post-Estimation Diagnostic Tests for Environmental Sustainability Model

Test Statistics	Test Type	Value	Probability
Wald Test	F-statistic	5.8075	0.0269
Normality Test	Jarque-Bera	0.8067	0.6680
Serial Correlation	Breusch-Godfrey LM (F-statistic)	0.2389	0.7902
Heteroskedasticity	Breusch-Pagan-Godfrey (F-statistic)	0.3548	0.9423
Functional Form	Ramsey RESET (F-statistic)	0.7555	0.3968

Source: Author's Computation (2026).

The post-estimation diagnostic results presented in Table 4.10 confirm the adequacy and reliability of the estimated ARDL model for environmental sustainability. The Wald test reports an F-statistic of 5.808 with a probability value of 0.0269, indicating that the explanatory variables are jointly significant in explaining variations in environmental sustainability. Consequently, the null hypothesis of joint insignificance is rejected at the 5% significance level.

The Jarque-Bera statistic produces a probability value of 0.6680, indicating that the residuals are normally distributed. Therefore, the null hypothesis of normality cannot be rejected. The Breusch-Godfrey Serial Correlation LM test reports a probability value of 0.7902, suggesting the absence of serial correlation among the residuals. Likewise, the Breusch-Pagan-Godfrey heteroskedasticity test yields a probability value of 0.9423, indicating that the residuals are homoskedastic and possess constant variance. Furthermore, the Ramsey RESET test reports a probability value of 0.3968, implying that the null hypothesis of correct model specification cannot be rejected. This indicates that the estimated functional form is correctly specified and that no significant omitted variable bias exists.

4.3 Discussion of Findings

The findings reveal that Information and Communication Technology (ICT) exerts significant but heterogeneous effects across the three dimensions of sustainability in Nigeria. The positive and statistically significant effect of ICT on economic sustainability indicates that improvements in digital infrastructure, internet penetration, and communication technologies enhance productivity, stimulate innovation, reduce transaction costs, and facilitate efficient resource allocation, thereby promoting sustained economic growth. This finding corroborates the empirical evidence of Onuogu et al. (2024), who reported that ICT diffusion significantly enhances economic growth in Sub-Saharan Africa by improving productivity and complementing trade openness and globalization. Similarly, Salahuddin et al. (2021) found that ICT development stimulates long-run economic growth through improvements in technological innovation and production efficiency across developing economies. The finding is also consistent with the endogenous growth theory, which identifies technological progress as a major determinant of sustained economic growth.

The results further indicate that ICT exerts a positive and statistically significant influence on social sustainability, implying that increased ICT penetration improves human development through greater access to education, healthcare, financial services, information dissemination, and employment opportunities. The result suggests that digital technologies strengthen social inclusion and improve overall welfare. This finding agrees with Asongu and Le Roux (2017), who

established that ICT significantly enhances inclusive human development in African countries by expanding access to knowledge and reducing social exclusion. Likewise, Asongu and Odhiambo (2020) reported that ICT contributes positively to human development through improvements in education, health outcomes, and financial inclusion.

With respect to environmental sustainability, ICT was found to reduce carbon dioxide emissions significantly in both the short run and the long run, indicating that digital technologies contribute to environmental sustainability by improving energy efficiency, facilitating cleaner production techniques, reducing resource wastage, and supporting smart environmental management systems. This finding corroborates Onuogu et al. (2024), who observed that ICT adoption contributes to sustainable development by promoting efficient resource utilization and cleaner production systems in Sub-Saharan Africa. However, the finding contrasts with Danish et al. (2019), who reported that ICT expansion may initially increase electricity consumption and carbon emissions in developing economies due to increased demand for digital infrastructure before environmental gains are realized through technological efficiency improvements.

Gross Fixed Capital Formation (GFCF) exhibits mixed effects across the sustainability dimensions. The variable positively influences social sustainability but remains statistically insignificant in explaining both economic sustainability and environmental sustainability. The positive contribution to human development suggests that infrastructure investment improves access to education, healthcare, transportation, and other social services. However, the insignificant effect on economic sustainability implies that physical capital investment has not generated the expected productivity gains, possibly because of inefficient investment allocation and inadequate complementary infrastructure. This finding contrasts with the predictions of endogenous growth theory, which argues that capital accumulation should stimulate sustained economic growth, but supports empirical studies showing that the effectiveness of capital investment depends on institutional quality and investment efficiency.

Human capital demonstrates a positive and statistically significant contribution to both economic sustainability and social sustainability. This finding indicates that improvements in education and workforce skills enhance labour productivity, stimulate innovation, and improve human welfare. The result corroborates Adeyemo (2026), who found that improvements in human capital significantly strengthen industrial development and enhance the gains derived from globalization in Nigeria. Conversely, human capital was found to increase carbon dioxide emissions significantly. This suggests that improvements in educational attainment have been accompanied by expanded industrial and productive activities that remain largely dependent on fossil-fuel energy sources. The result therefore implies that human capital development alone may not guarantee environmental sustainability unless accompanied by cleaner technologies and renewable energy adoption.

Trade openness was found to exert contrasting effects across the three sustainability dimensions. The positive and significant influence on economic sustainability indicates that integration into international markets promotes economic growth through technology transfer, expanded export opportunities, improved competitiveness, and efficient resource allocation. This finding corroborates Nwadike et al. (2020), who found that trade openness significantly promotes economic growth in Nigeria. Similarly, Omoke and Opuala-Charles (2021) concluded that trade openness enhances economic growth where supported by sound institutional quality.

However, trade openness exhibits a negative and statistically significant long-run effect on social sustainability, suggesting that although globalization stimulates economic activities, its benefits may not be distributed equitably across society. This finding implies that greater openness may widen disparities in access to employment and social services when redistributive policies are weak. In contrast, Ogede and Tiamiyu (2021) reported that trade openness contributes positively to sustainable development in Nigeria, indicating that the social effects of openness may depend on the extent to which complementary social and institutional policies are implemented. Furthermore, the long-run effect of trade openness on environmental sustainability was found to be statistically insignificant, suggesting that international trade has not been a dominant determinant of environmental quality after accounting for ICT, human capital, and investment.

5. CONCLUSION AND RECOMMENDATIONS

This study examined the effect of Information and Communication Technology (ICT) on sustainable development in Nigeria by investigating its influence on the three fundamental dimensions of sustainability, namely economic sustainability, social sustainability, and environmental sustainability. Based on the empirical evidence, it is concluded that Information and Communication Technology constitutes a significant driver of sustainable development in Nigeria. ICT significantly promotes economic sustainability by enhancing productivity, innovation, and economic efficiency. It also improves social sustainability through enhanced human development arising from increased access to information, education, healthcare services, and digital opportunities. Furthermore, ICT contributes positively to environmental sustainability by reducing carbon dioxide emissions through improved energy efficiency and technological innovation.

Based on the findings and conclusions of the study, the following recommendations are advanced:

- The Federal Government should prioritize investments in digital infrastructure and expand ICT penetration across both urban and rural communities. Greater investment in broadband infrastructure, digital connectivity, and affordable internet services will facilitate technological innovation, improve productivity, and enhance long-term economic sustainability.
- Government should strengthen digital inclusion policies by integrating ICT into education, healthcare, and public service delivery. Expanding digital literacy programmes and improving access to online educational and healthcare platforms will further enhance human development and promote social sustainability.
- Environmental policies should encourage the adoption of ICT-enabled green technologies and smart production systems. Incentives such as tax relief, investment credits, and public-private partnerships should be introduced to encourage firms to adopt energy-efficient technologies, digital monitoring systems, and environmentally sustainable production processes capable of reducing carbon emissions.
- Energy and industrial policies should accelerate Nigeria's transition towards renewable energy and cleaner production technologies. Greater investment in renewable energy infrastructure, energy-efficient production systems, and low-carbon technologies will enable improvements in human capital and industrial productivity to occur without increasing environmental degradation.

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