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FINANCIAL DEVELOPMENT, ENERGY CONSUMPTION, DIGITALIZATION, AND CARBON EMISSIONS IN NIGERIA

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ABSTRACT

The key role digitalization plays in reshaping the relationship between financial development, energy consumption, and carbon emissions in Nigeria from 1990 to 2023 is examined. While previous studies investigated the independent relationship between these variables, limited evidence exists in developing economies on the moderating role of digitalization. Three complementary models are estimated employing the autoregressive distributed lag methodology to examine the direct impacts of financial development and energy consumption, digitalization's independent contribution, and its moderating influence on the finance-energy-environment nexus. The findings reveal mixed environmental effects of financial development, where it is emissions-reducing in the short run but displays an insignificant long-run impact. Fossil fuel consumption is significantly emissions-promoting, whereas renewable energy consumption limits emissions, contributing to improved environmental outcomes. While digitalization displays no significant long-run direct effect on emissions, its moderating role is crucial as it amplifies the environmental degradation role associated with fossil fuel consumption, revealing a digitization-emission trap. Likewise, promoting the emissions-limiting effect of renewable energy consumption. The results also demonstrate that economic growth contributes to lower emissions in the long run. The finance-energy-environment literature is extended by demonstrating how digitalization functions beyond merely being an independent determinant of environmental quality but also functions as a critical conditioning mechanism. The findings emphasize the need to integrate green finance, renewable energy, and sustainable digital infrastructure to facilitate Nigeria's transition to a low-carbon economy.

Keywords: Financial Development; Digitalization; Renewable Energy; Carbon Emissions; Nigeria

JEL Classification: O16; O33; Q43; Q56; O55

1. Introduction

In this digital age, aligning economic growth with environmental sustainability has become a pressing developmental issue. Greater attention has been placed on decoupling the economic growth process from carbon-intensive production systems. Incidentally, countries strive to attain the 2030 Agenda for Sustainable Development and the Paris Agreement. Primarily focused on the attainment of SDGs 7, 9, and 13, which promote clean energy, sustainable industrialization, and climate action (Sheraz et al., 2022). Despite these commitments, attaining environmental sustainability remains a persistent policy challenge due to the continuous dependence on fossil fuel-driven growth by developing economies.

One of the major drivers of climate change, contributing to over 60% of global greenhouse gases, is carbon dioxide (CO₂) emissions (Acheampong, 2019). Despite global carbon neutrality commitments, energy-related carbon emissions (hereafter, emissions) persist, as developing economies continuously rely on fossil fuel-driven growth. Thus, environmental pressures are intensified by rising energy demands, industrialization, and urbanization (Ihezukwu et al., 2025; Olaoye et al., 2025). In order to attain sustainable development, the need to understand the macroeconomic drivers of emissions is paramount.

Financial development is acknowledged as one of these drivers. Financial development influences energy demand, investment, production, and technological innovation, though its environmental implications are theoretically and empirically ambiguous. Financial deepening, according to traditional growth theory, eventually increases fossil fuel use and emissions via its access to credit expansion, investment, and consumption stimulation process (Sadorsky, 2010, 2011). On the other side of the argument, in line with the green finance perspective, efficient financial systems improve environmental quality via renewable energy investment facilitation, green innovation, and cleaner production technologies (Anton & Afloarei Nucu, 2020; Kim & Park, 2016; Tamazian et al., 2009). The mixed empirical evidence explains the competing mechanisms, which suggest that financial development's environmental effects are dependent on energy, technological, and institutional conditions (Chang, 2015; Usman et al., 2021).

Energy consumption is a key channel via which environmental sustainability is influenced by financial development. Fossil fuel predominates energy supply globally and remains the largest contributor to emissions. Unlike fossil fuel, renewable energy is integral to sustainable development and low-carbon transition policies (Anton & Afloarei Nucu, 2020; Mukhtarov et al., 2020). The share in the national energy mix, energy improvement efficiency, and technological process all determine to what degree renewable energy is beneficial environmentally (Kar & Bali Swain, 2024; Nguyen & Kakinaka, 2019). Thus, to get a stronger understanding of the energy-environment nexus, the need arises to distinguish renewable energy from fossil fuel consumption instead of aggregate energy measures.

Digitalization is another important determinant of environmental outcomes. Financial inclusion, energy efficiency, and green innovation have all been enhanced by the surging development of information and communication technologies, mobile connectivity, digital financial services, and artificial intelligence production systems (Huang et al., 2022; Ke et al., 2022). Digital infrastructure, telecommunications networks, and data centres all require considerable consumption of electricity. This implies that digitalization may either moderate or exacerbate emissions depending on the prevalent energy mix (Dimian et al., 2025; Le & Pham, 2024). Thus, Digitalization is not only an independent

determinant of environmental sustainability, but also a mechanism via which the finance-energy nexus influences emissions.

As Africa's largest economy, Nigeria simultaneously experiences rapid financial sector development and digital transformation, alongside persistent energy poverty and environmental degradation (Dimnwobi et al., 2022; Ihezukwu et al., 2025; Udo et al., 2025). About 77 million Nigerians lack access to electricity despite the country's abundance in oil and gas resources. Accompanied by the persistent upward trend in emissions due to fossil fuels being the dominant source of energy (Dimnwobi et al., 2022). On the other hand, the country's economy is continuously reshaped by banking sector reforms, financial inclusion, mobile telecommunications, internet penetration, and fintech innovations (Dimnwobi et al., 2022; Olayiwola, 2024). Therefore, an important policy question is raised based on these developments: can Nigeria's transition to a low-carbon economy be facilitated by financial development and digitalization without hindering economic development?

While the finance-environment, energy-environment, and digitalization-environment nexuses have been extensively examined, evidence remains divided. Most studies independently examine these factors, thus overlooking their interconnected relationships (Chang, 2015; Zhang et al., 2026). Some conclude that financial development and digitalization promote environmental degradation. Others argue that they facilitate renewable energy adoption, energy efficiency, and technological innovation (Anton & Afloarei Nucu, 2020; Huang et al., 2022; Ke et al., 2022; Le & Pham, 2024; Yu et al., 2022, 2023). Evidence from Nigeria is even more scarce. With limited attention applied to distinguishing fossil fuel from renewable energy consumption. Likewise, investigating whether digitalization moderates the environmental effects of financial development and energy use.

These identified gaps are addressed by this study by examining the relationships between financial development, fossil fuel consumption, renewable energy consumption, digitalization, and carbon emissions in Nigeria from 1990 to 2023.

Research Questions

The research questions of the study are as follows:

- a) What are the short-run and long-run effects of financial development, energy consumption, and digitalization on carbon emissions in Nigeria?
- b) Does digitalization moderate the environmental effects of the finance-energy nexus in Nigeria?

Objectives of the Study

Against this backdrop, precisely, the study seeks to:

- a) examine the short-run and long-run effects of financial development, energy consumption, and digitalization on carbon emissions in Nigeria (distinguishing between fossil and renewable energy sources).
- b) investigate the moderating role of digitalization in the finance-energy-environment nexus in Nigeria.

The study employs the autoregressive distributed lag (ARDL) framework to achieve these objectives by estimating both the short-run and long-run relationships. Robust and policy-relevant evidence on how Nigeria's transition towards a low-carbon economy can be facilitated via strategic alignment of financial development, energy transition, and digital transformation is generated by the framework.

The remainder of the study is organized as follows. Section 2 reviews the conceptual, theoretical, and empirical literature. Section 3 presents the theoretical framework, model specification, data, and

estimation methodology. Section 4 reports and discusses the empirical findings. Finally, Section 5 concludes with the major policy recommendations.

2. Literature Review

2.1 Conceptual Literature

Financial development, energy consumption, digitalization, and carbon emissions constitute an interlinked mechanism influencing environmental sustainability. Financial development refers to financial institutions and markets improvements which facilitate savings mobilization and capital allocation for productive investment (Svirydzenka, 2016). Financing industrialization and renewable technologies adoption; therefore, its environmental impact depends on efficient resource allocation (Acheampong, 2019; Ma et al., 2022). Energy consumption refers to the use of fossil fuel and renewable energy in economic activities and it is the primary channel via which financial development influences environmental quality; while emissions are increased by fossil fuels, renewable energy facilitates decarbonization and sustainable development, although its effectiveness is dependent on complementary factors such as financial inclusion and technological progress which reduce energy poverty and improves access to clean energy technologies (Anton & Afloarei Nucu, 2020; Asongu & Odhiambo, 2023; Koomson & Danquah, 2021; Mukhtarov et al., 2020). Digitalization is the adoption of digital technologies that facilitate the improvement of financial inclusion, resource allocation, and energy efficiency, but may stimulate emissions where electricity generation is predominantly fossil fuel-driven (Dimian et al., 2025; Huang et al., 2022; Ke et al., 2022; Zhang & Wang, 2023). Finally, carbon emissions are the predominant anthropogenic greenhouse gas and serve as a measure for environmental quality and sustainability (Acheampong, 2019).

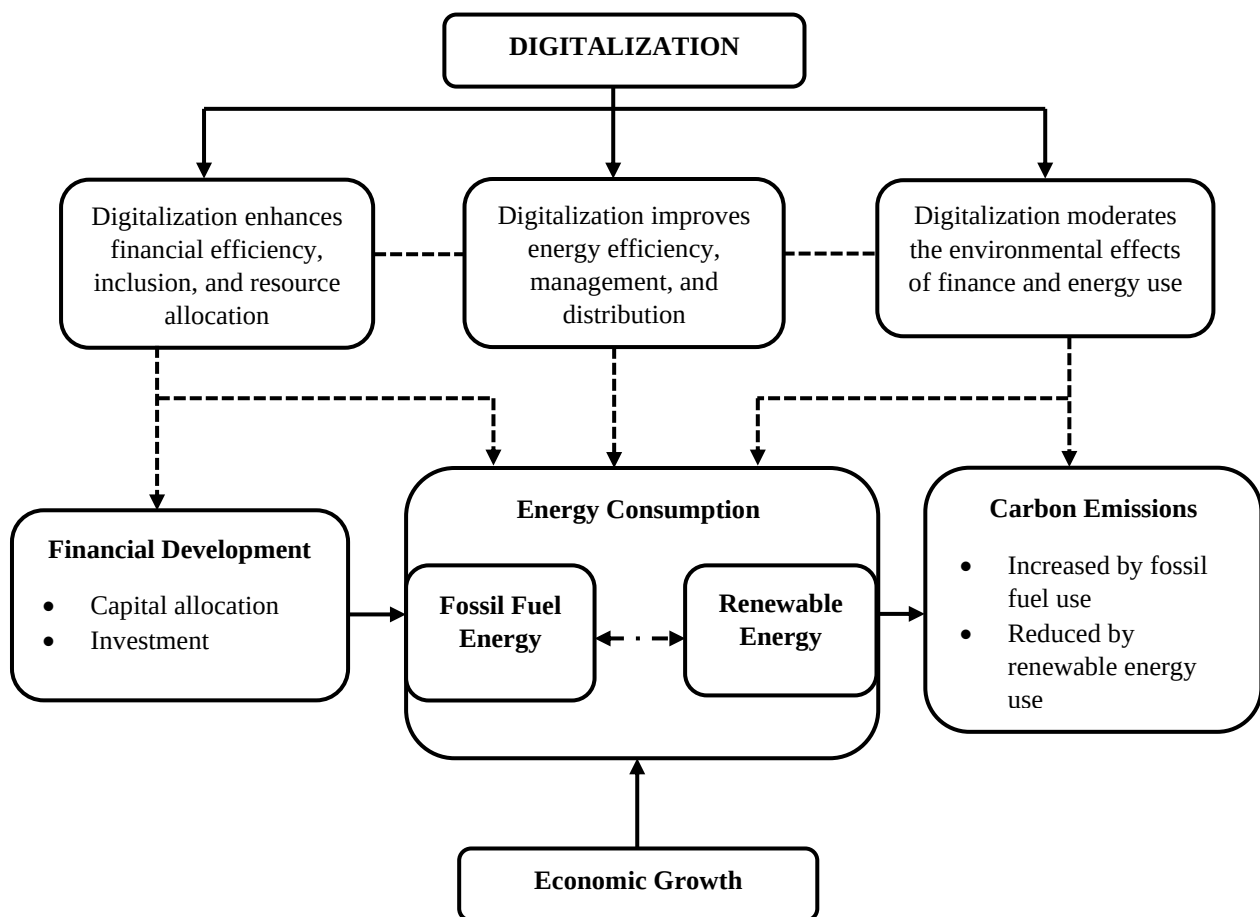


Figure 1. Conceptual Framework of the Finance-Energy-Digitalization-Emissions Nexus

Source: Authors' Conceptualization based on Dietz and Rosa (1997), Goldsmith (1969), Grossman and Krueger (1995), McKinnon (1973), and Shaw (1973).

Consequently, this study conceptualizes emissions as the outcome of the interactions between financial development, fossil fuel consumption, renewable energy consumption, and digitalization (see Figure 1). Capital allocation is determined by financial development, with energy consumption representing the primary transmission channel. Finally, digitalization functions as both an independent determinant and moderator of environmental outcomes.

2.2 Theoretical Literature

Environmental sustainability is measured using CO₂ emissions, which are the primary contributor to global warming (Acheampong, 2019). This relationship is illustrated by the environmental Kuznets curve (EKC) hypothesis through scale, composition, and technique effects. The EKC hypothesis proposes an inverted U-shaped relationship between development and environmental degradation (Grossman & Krueger, 1995; Stern, 2004; Wang et al., 2025). The finance-environment literature also complements the EKC hypothesis by identifying how financial development influences energy demand and emissions via the direct, business, and wealth effect mechanisms (Mahalik et al., 2017; Sadorsky, 2010, 2011). These mechanisms align with the stochastic impacts by regression on population, affluence, and technology (STIRPAT) framework. This framework links changes in environmental quality to socioeconomic and technological factors such as financial development, renewable energy consumption, and digitalization (Dietz & Rosa, 1997; Udo et al., 2025).

2.3 Empirical Literature

The finance-environment nexus remains inconclusive, with empirical evidence centered on two dominant perspectives. The first argues that financial development is emissions-promoting via expansion of industrial production, household consumption, and fossil fuel use (Ihezukwu et al., 2025; Sadorsky, 2010, 2011). In contrast, the second contends that financial development promotes environmental sustainability via financing renewable energy, green innovation, and cleaner technologies (Anton & Afloarei Nucu, 2020; Kim & Park, 2016; Tamazian et al., 2009). Recent studies (e.g., Mahalik et al., 2017) identified nonlinear effects influenced by institutional quality, financial improvement, and technological progress.

Energy consumption constitutes the primary mechanism via which environmental outcomes are influenced by financial development. While improved access to finance generally raises energy demand by facilitating investment and production (Mukhtarov et al., 2018; Sadorsky, 2011), advanced financial systems also improve energy efficiency and renewable energy adoption, therefore mitigating emissions (Anton & Afloarei Nucu, 2020; Farhani & Solarin, 2017; Lahiani et al., 2021; Mukhtarov et al., 2020). By easing long-term financing constraints and reducing investment risks, renewable energy deployment is further facilitated by financial development (Lahiani et al., 2021; Mukhtarov et al., 2020; Qayyum et al., 2021). The environmental benefits of renewable energy lie contingently on institutional quality, infrastructure development, and degree of financial inclusion (Gu, 2024; Jin et al., 2024; Kar & Bali Swain, 2024; Koomson & Danquah, 2021; Nguyen & Kakinaka, 2019).

Digitalization is another important determinant of environmental sustainability with contrasting effects. Energy efficiency, green finance, renewable energy adoption, and resource allocation are improved by digital technologies (Saqib et al., 2023; Touati & Ben-Salha, 2024). Conversely, in fossil fuel-dependent economies, digital infrastructure expansion also raises electricity demand and emissions (Onyeneke et al., 2024). Recent evidence indicates that digitalization moderates the finance-environment nexus, where technological readiness and energy mix are key determinants of environmental outcomes (Huang et al., 2022; Le & Pham, 2024).

Evidence from Nigeria remains divided and often contradictory. Where financial development exacerbates environmental degradation (Ihezukwu et al., 2025), whereas renewable energy investment is facilitated via clean energy and sustainable development investment (Dimnwobi et al., 2022). Likewise, although digitalization improves sustainable development and financial inclusion (Olayiwola, 2024; Udo et al., 2025), digital infrastructure expansion raises emissions via fossil fuel-dependent electricity generation (Tukur et al., 2026).

Despite growing evidence, four gaps remain in Nigerian literature. First, the finance-energy-digitalization nexus is examined independently rather than within a combined framework. Second, energy consumption is measured in an aggregate term, obscuring the distinct environmental impacts of fossil fuel and renewable energy consumption. Third, limited evidence exists on the moderating role of digitalization in the finance-energy-environment nexus. Finally, the examination of Nigeria's financial reforms, digital transformation, and energy transition from 1990 to 2023 is limited.

Consequently, this study contributes to the existing literature by developing a framework that examines financial development, energy consumption, digitalization, and carbon emissions in Nigeria. This study distinguishes between fossil fuel and renewable energy sources, while evaluating the moderating role of digitalization. Contemporary evidence in Nigeria is provided by this study to inform policies on green finance, digital transformation, renewable energy, and environmental sustainability.

3. Methodology

The EKC hypothesis, financial intermediation theory, and STIRPAT framework form the theoretical foundation for modelling how carbon emissions in Nigeria are jointly influenced by financial development, energy consumption, and digitalization. According to these theories, environmental sustainability is shaped by the interactions between economic development, financial systems, technological progress, and energy transition rather than by an individual determinant (Dietz & Rosa, 1997; Grossman & Krueger, 1995).

EKC Hypothesis

An inverted U-shaped relationship between economic growth and environmental degradation is posited by the EKC hypothesis. Where industrialization raises pollution at the initial stages of development via its scale effect. Subsequently, increased income levels facilitate the adoption of cleaner technologies, structural transformation, and robust environmental regulations aimed at improving environmental quality (Grossman & Krueger, 1995; Stern, 2004). The EKC is conventionally expressed as:

$$CE_t = \beta_0 + \beta_1 PCI_t + \beta_2 PCI_t^2 + \varepsilon_t \quad (3.1)$$

Where CE denotes carbon emissions, PCI represents GDP per capita growth, and ε_t is the stochastic error term.

Financial development, technological progress, and energy composition in developing economies shape environmental sustainability according to recent studies (Acheampong, 2019; Wang et al., 2025).

Financial Intermediation Theory

Financial intermediation theory illustrates how efficient financial systems mobilize savings and allocate capital to productive investments (Goldsmith, 1969; McKinnon, 1973; Shaw, 1973). Financial development plays a dual role where it reduces emissions by financing renewable energy and green technologies. Likewise, it may also raise pollution via fossil fuel facilitated credit expansion (Mahalik et al., 2017; Sadorsky, 2010, 2011; Tamazian et al., 2009). Thus,

$$CE_t = \beta_0 + \beta_1 FD_t + \beta_2 FEC_t + \beta_3 REC_t + \beta_4 PCI_t + \varepsilon_t \quad (3.2)$$

Where FD denotes financial development, FEC is fossil fuel energy consumption, and REC represents renewable energy consumption.

STIRPAT Framework

The IPAT identity is extended by the STIRPAT framework to allow environmental outcomes to respond flexibly to socioeconomic and technological factors. Digitalization has been incorporated as a primary determinant of environmental sustainability according to recent studies (Ke et al., 2022; Zhang & Wang, 2023). Hence,

$$CE_t = \beta_0 + \beta_1 FD_t + \beta_2 FEC_t + \beta_3 REC_t + \beta_4 DI_t + \beta_5 PCI_t + \varepsilon_t \quad (3.3)$$

Where DI denotes digitalization.

Recent evidence hints at the moderating role of digitalization on the environmental effects of finance and energy consumption (Ke et al., 2022; Le & Pham, 2024; Zhang et al., 2026). Therefore,

$$CE_t = \beta_0 + \beta_1 (FD * DI)_t + \beta_2 (FEC * DI)_t + \beta_3 (REC * DI)_t + \beta_4 PCI_t + \varepsilon_t \quad (3.4)$$

The ARDL bounds testing approach by Pesaran et al. (2001) is employed in this study to estimate both short-run dynamics and long-run equilibrium relationships. The ARDL is appropriate as it accommodates variables with mixed order of integration, that is, integrated of order $I(0)$ and $I(1)$. It also performs well with relatively small sample sizes where it simultaneously estimates the error correction model (ECM) and the long-run equilibrium coefficients (Nkoro & Uko, 2016; Pesaran et al., 2001). The ARDL is widely applied in studies examining the finance-energy-environment nexus due to its telling advantages (Kirikkaleli & Adebayo, 2021; Le & Pham, 2024; Udo et al., 2025).

To progressively investigate the finance-energy-digitalization-environment nexus, three ARDL specifications are estimated.

Model 1: Baseline Specification

The conventional relationship between financial development, energy consumption, economic growth, and carbon emissions is evaluated in the baseline model. Hence,

$$\begin{aligned} \Delta \ln CE_t = & \alpha_0 + \alpha_{1i} \ln CE_{t-i} + \alpha_{2i} FD_{t-i} + \alpha_{3i} FEC_{t-i} + \alpha_{4i} REC_{t-i} + \alpha_{5i} PCI_{t-i} + \\ & \sum_{i=1}^4 \beta_{1i} \Delta \ln CE_{t-i} + \sum_{i=1}^4 \beta_{2i} \Delta FD_{t-i} + \sum_{i=1}^4 \beta_{3i} \Delta FEC_{t-i} + \sum_{i=1}^4 \beta_{4i} \Delta REC_{t-i} + \sum_{i=1}^4 \beta_{5i} \Delta PCI_{t-i} + \\ & \lambda EC_{t-1} + \varepsilon_t \end{aligned} \quad (3.5)$$

Where EC is the error correction term, and $\ln$ denotes the natural logarithm.

Model 2: Digitalization Specification

Digitalization is introduced to the second specification to account for its direct contribution to environmental quality after controlling for financial development and energy consumption. Therefore,

$$\Delta \ln CE_t = \alpha_0 + \alpha_{1i} \ln CE_{t-i} + \alpha_{2i} FD_{t-i} + \alpha_{3i} FEC_{t-i} + \alpha_{4i} REC_{t-i} + \alpha_{5i} \ln DI_{t-i} + \alpha_{6i} PCI_{t-i} + \sum_{i=1}^3 \beta_{1i} \Delta \ln CE_{t-i} + \sum_{i=1}^3 \beta_{2i} \Delta FD_{t-i} + \sum_{i=1}^3 \beta_{3i} \Delta FEC_{t-i} + \sum_{i=1}^3 \beta_{4i} \Delta REC_{t-i} + \sum_{i=1}^3 \beta_{5i} \Delta \ln DI_{t-i} + \sum_{i=1}^3 \beta_{6i} \Delta PCI_{t-i} + \lambda EC_{t-1} + \varepsilon_t \quad (3.6)$$

Model 3: Moderating Specification

The interaction terms are introduced to the final model to investigate whether digitalization moderates the environmental effects of financial development and energy consumption. Thus,

$$\Delta \ln CE_t = \alpha_0 + \alpha_{1i} \ln CE_{t-i} + \alpha_{2i} (FD * \ln DI)_{t-i} + \alpha_{3i} (FEC * \ln DI)_{t-i} + \alpha_{4i} (REC * \ln DI)_{t-i} + \alpha_{5i} PCI_{t-i} + \sum_{i=1}^3 \beta_{1i} \Delta \ln CE_{t-i} + \sum_{i=1}^3 \beta_{2i} \Delta (FD * \ln DI)_{t-i} + \sum_{i=1}^3 \beta_{3i} \Delta (FEC * \ln DI)_{t-i} + \sum_{i=1}^3 \beta_{4i} \Delta (REC * \ln DI)_{t-i} + \sum_{i=1}^3 \beta_{5i} \Delta PCI_{t-i} + \lambda EC_{t-1} + \varepsilon_t \quad (3.7)$$

The empirical basis for evaluating whether digital transformation promotes or hinders the environmental consequences of financial development, fossil fuel dependence, and renewable energy transition is provided by the interaction terms.

The ARDL framework, under correct model specification, mitigates against potential endogeneity problems resulting from reverse causality by minimising the contemporaneous feedback via the inclusion of lagged dependent and independent variables, alongside the error correction mechanism. Likewise, the ARDL framework inherently moderates structural shifts via its dynamic lag structure. Hence, producing consistent long-run estimates even in the presence of endogenous regressors and structural breaks (Harris & Sollis, 2003; Pesaran et al., 2001). The relatively small sample size hints against the inclusion of structural break dummy variables, which would reduce estimation efficiency and result in overparameterization.

This study utilizes annual time series data covering the period from 1990 to 2023. Nigeria's financial reforms, digital transformation, and energy transition are captured in this period while also accounting for complete observations.

Table 1. Measurement of Variables and Data Sources

Variable	Acronym	Proxy	Measurement	Source
Carbon Emissions	CE	CO ₂ emissions	Total million tonnes (MtCO ₂)	World Development Indicators (2025)
Financial Development	FD	Domestic credit to private sector	% of GDP	World Development Indicators (2025)
Fossil Fuel Energy Consumption	FEC	Fossil fuel energy use	% of total energy consumption	World Development Indicators (2025)
Renewable Energy Consumption	REC	Renewable energy consumption	% of total final energy consumption	World Development Indicators (2025)
Digitalization	DI	Mobile cellular subscriptions	Total	World Development Indicators (2025)
Economic Growth	PCI	GDP per capita growth	Annual %	World Development Indicators (2025)

Source: Authors' Computation (2026)

These indicators are widely employed in environmental and development economics as they provide consistent and adequate measures of financial development, energy transition, technological progress, and emissions (Acheampong, 2019; Dimian et al., 2025; Ke et al., 2022; Wang et al., 2025). Proxying

digitalization with mobile cellular subscriptions adequately captures Nigeria’s mobile-driven digital transformation. Nigeria’s digital space is dominated by mobile platforms. This indicator also provides consistent, uninterrupted observations and is adopted in other digitalization-infrastructure-environmental studies in developing economies (Asongu, 2018; Onyeneke et al., 2024). Proxying financial development with credit to the private sector appropriately captures the primary channel via which finance directly influences energy consumption and emissions. Given Nigeria’s bank-dominated financial system, where private sector activity is the main driver of economic growth. This is also adopted in developing economies' environmental literature (Acheampong, 2019; Aderajo & Akintunde, 2022; Boutabba, 2014; Sadorsky, 2010; Shahbaz et al., 2013).

4. Results and Discussion of the Findings

4.1 Result Presentation

Descriptive Statistics

Table 2. Descriptive Statistics

Variable	CE	FD	FEC	REC	DI	PCI
Mean	103.5874	10.56511	50.80520	84.28137	72280816	1.578845
Median	102.9259	10.06369	51.44000	84.50000	36358900	1.502197
Maximum	130.9817	19.62560	58.23000	88.60000	2.24E+08	12.21039
Minimum	75.10730	4.957522	42.39000	79.90000	0.001000	-4.59723
Std. Dev.	16.48775	3.674392	4.607887	2.712785	79905024	3.701238
Skewness	0.177899	0.699921	-0.27989	-0.13953	0.583908	0.499591
Kurtosis	1.851979	2.940485	1.948352	1.671800	1.815016	3.637496
Jarque-Bera	2.046439	2.781057	2.010711	2.609489	3.921303	1.990086
Probability	0.359436	0.248944	0.365914	0.271242	0.140767	0.369708
Sum	3521.971	359.2139	1727.377	2865.567	2.46E+09	53.68075
Sum Sq. Dev.	8970.919	445.5382	700.6766	242.8538	2.11E+17	452.0723
Observations	34	34	34	34	34	34

Source: Authors’ Computation from Estimations using EViews (2026)

The variables of the study show considerable variations as indicated by the descriptive statistics (see Table 2). This reflects the structural evolution of the Nigerian economy, financial system, energy sector, and digital landscape over the study period. The largest dispersion is exhibited by digitalization; this is consistent with the rapid expansion of mobile and digital technologies. Emissions and financial development display moderate variability. Whereas energy consumption (fossil fuel and renewable) remains comparatively stable. This suggests that changes in the Nigerian energy mix have been gradual rather than transformative. Economic growth experienced visible fluctuations, showing alternating periods of economic boom and contraction. The variables exhibited satisfactory distributional properties with no significant evidence of nonnormality.

Multicollinearity Tests

Table 3. Pairwise Correlation Matrix

	CE	FD	FEC	REC	DI	PCI
CE	1.00	0.39	0.74	-0.94	0.83	-0.16
FD	0.39	1.00	0.30	-0.40	0.66	0.06
FEC	0.74	0.30	1.00	-0.87	0.72	-0.07

REC	-0.94	-0.40	-0.87	1.00	-0.81	0.07
DI	0.83	0.66	0.72	-0.81	1.00	-0.21
PCI	-0.16	0.06	-0.07	0.07	-0.21	1.00

Source: Authors' Computation from Estimations using EViews (2026)

The pairwise correlation results are in alignment with theoretical expectations (see Table 3). Emissions are positively related to fossil fuel consumption and digitalization, but share an inverse relationship with renewable energy. Whereas financial development shows a weak direct relationship with emissions, while economic growth reflects a weak indirect relationship.

Table 4. Variance Inflation Factors

Variable	Model 1	Model 2	Model 3
FD	1.208336	1.800523	
FEC	4.018560	4.403562	
REC	4.343032	5.452297	
LNDI		2.311585	
PCI	1.012577	1.012590	1.029861
FD*LNDI			4.093050
FEC*LNDI			21.96155
REC*LNDI			21.51145

Source: Authors' Computation from Estimations using EViews (2026)

The variance inflation factors (VIFs) show that most correlations fall well below the conventional threshold of 10, with a couple of exceptions (see Table 4). Indicating the absence of serious multicollinearity in the baseline and digitalization models. While higher values are expected in the interaction terms, this does not invalidate the estimates.

Table 5. Unit Root Test

Variable	ADF	PP	ZA	ADF	PP	ZA	Remark
	t-stat	Adj t-stat	t-stat	t-stat	Adj t-stat	t-stat	
	Levels			First Difference			
LNCE	-1.8263	-1.8263	-4.0992	-6.2762*	-6.4827*	-7.3783*	I(1)
FD	-2.0813	-1.3285	-5.2660**	-4.2150*	-4.9420*		I(0/1)
FEC	-2.0934	-2.0523	-4.5466	-5.6022*	-6.7016*	-6.1673*	I(1)
REC	-1.5734	-1.5615	-3.8338	-6.0899*	-6.1036*	-6.6031*	I(1)
LNDI	-11.5710*	-5.8092*	-19.5424*				I(0)
PCI	-3.8671*	-3.9937*	-3.6479			-5.3493*	I(0/1)
FD*LNDI	-1.3731	-1.0024	-4.2305	-4.3672*	-4.7005*	-5.8635*	I(1)
FEC*LNDI	-2.6399	-3.6021*	-3.3091	-6.3090*		-7.3025*	I(0/1)
REC*LNDI	-6.2102*	-6.2902*	-4.2364			-5.2414*	I(0/1)

Source: Authors' Computation from Estimations using EViews (2026)

Note. () signifies 1% level of significance, (**) signifies 5% level of significance, and (***) signifies 10% level of significance. Where, ADF is the Augmented Dickey-Fuller Test, PP is the Phillips-Perron Test, and ZA is the Zivot-Andrews Test. I(0) is integrated of order zero; I(1) is integrated of order one.

The ADF, PP, and ZA tests are used to examine the unit root properties of the variables (see Table 5), with the tests showing consistent evidence of mixed orders of integration. Based on the ADF and PP tests, carbon emissions, financial development, fossil fuel energy consumption, and renewable energy consumption are integrated of order one (become stationary after first difference). Digitalization and economic growth are integrated of order zero (stationary at levels). Finally, the interaction terms exhibited mixed orders of integration. With none of the variables integrated beyond the first order and all being of mixed order of integration, this satisfies the underlying requirement for the application of the ARDL bounds testing approach. The ZA test, which endogenously accounts for structural breaks, strengthens the robustness of the stationarity inference and shows that the variables are of mixed order of integration, with none exceeding I(1).

Table 6. Lag Length Selection Criteria

Model	Lag	LogL	LR	FPE	AIC	SIC	HQIC
Model 1	0	-237.787		7.363678	16.18582	16.41935	16.26053
	1	-175.973	98.90369	0.650145	13.73150	15.13270*	14.17976
	2	-150.415	32.37336	0.729001	13.69431	16.26317	14.51611
	3	-129.958	19.09256	1.525650	13.99722	17.73375	15.19257
	4	-64.0368	39.55292*	0.287290*	11.26912*	16.17331	12.83801*
Model 2	0	-309.563		27.98773	20.35889	20.63644	20.44937
	1	-214.575	147.0778*	0.652782	16.55323	18.49605*	17.18654*
	2	-174.033	47.08087	0.646357*	16.26021	19.86831	17.43636
	3	-127.526	36.00553	0.788933	15.58233*	20.85570	17.30132
Model 3	0	-597.971		5.40e+10	38.90138	39.13267	38.97677
	1	-525.096	117.5404	2.52e+09	35.81267	37.20040*	36.26503*
	2	-495.511	38.17415*	2.15e+09*	35.51686	38.06103	36.34620
	3	-465.413	29.12789	2.28e+09	35.18791*	38.88852	36.39422

Source: Authors' Computation from Estimations using EViews (2026)

Note. () indicates the lag order selected by the criterion (Model 1=4; Model 2=3; Model 3=3). Where LR is the sequential modified LR test statistic (each test at 5% level), FPE is Final prediction error, AIC is Akaike information criterion, SIC is Schwarz information criterion, and HQIC is Hannan-Quinn information criterion.

In time series analysis, the selection of optimal lag length is essential (particularly in autoregressive models). The preferred model specifications' lag lengths are selected using the AIC (see Table 6).

Table 7. Bounds Cointegration Test

F-Bounds Test	Null Hypothesis: No levels relationship				
Test Statistic	Value	Signif.	I(0)	I(1)	Remark
F-statistic (Model 1)	9.977446	1%	4.280	5.840	Cointegrated
F-statistic (Model 2)	24.02517	1%	4.134	5.761	Cointegrated
F-statistic (Model 3)	6.150005	1%	4.280	5.840	Cointegrated

Source: Authors' Computation from Estimations using EViews (2026)

*Note. K=4 (Model 1), K=5 (Model 2), K=4 (Model 3).

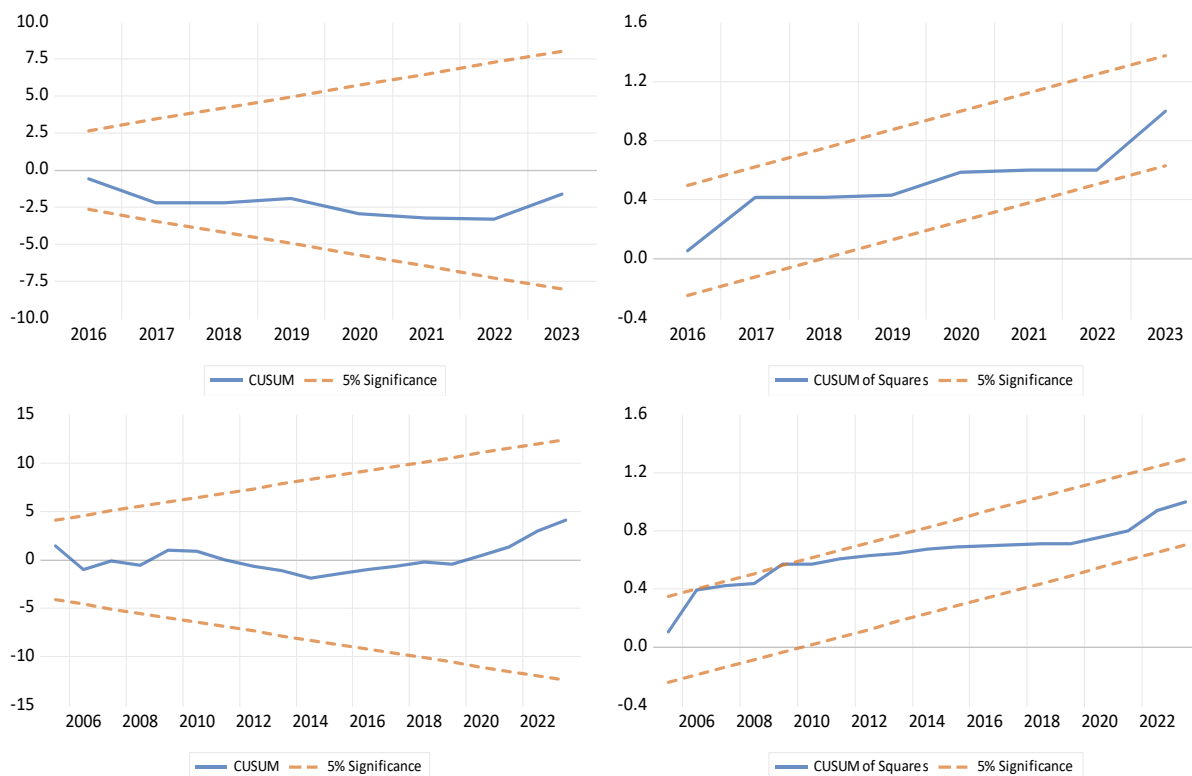
The bounds test confirms cointegration across all models (see Table 7). Indicating stable long-run equilibrium relationships and justifies estimation of both the long-run and short-run dynamics.

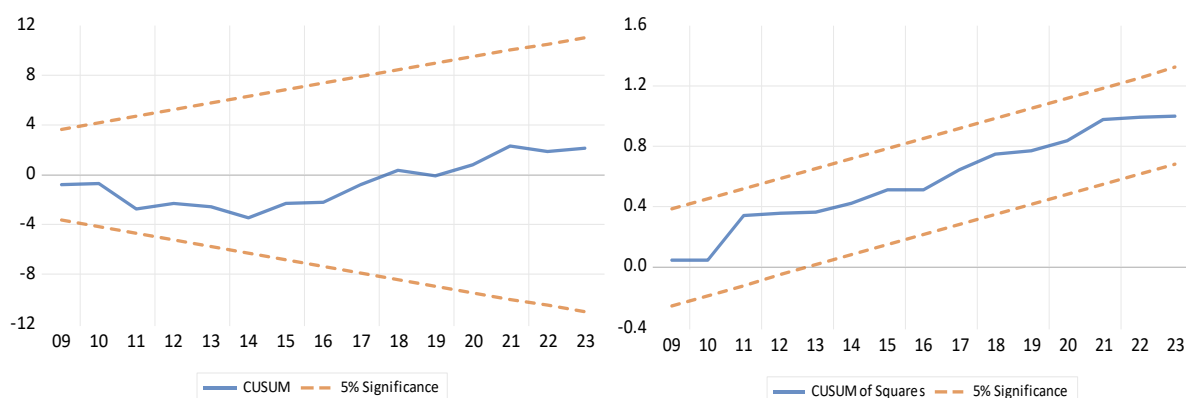
Table 8. Model Diagnostics

Test	Model 1	Model 2	Model 3
Breusch-Godfrey LM Test (p-value)	0.4415	0.7665	0.2293
Breusch-Pagan-Godfrey (p-value)	0.9840	0.4950	0.9296
ARCH Test (p-value)	0.3040	0.9620	0.9505
Jarque-Bera (p-value)	0.136579	0.255268	0.676455
Ramsey RESET (p-value)	0.1135	0.3286	0.0962

Source: Authors' Computation from Estimations using EViews (2026)

The robustness of the results is confirmed by the diagnostic and stability tests (see Table 8 and Figure 2). The standard assumptions of the ARDL framework for all the models are satisfied. The models demonstrate the absence of evidence of serial correlation, heteroskedasticity, nonnormality, and functional form misspecification. The CUSUM and CUSUMSQ tests confirm parameter stability throughout the study period, indicating the robustness of the ARDL estimates despite potential macroeconomic shocks. The estimated relationships are statistically reliable and suitable for policy inference, as indicated by these results (Nkoro & Uko, 2016; Perron, 1989; Pesaran et al., 2001; Rafindadi, 2016).

Figure 2. Cumulative Sum Tests



Source: Authors' Computation from Estimations using Eviews (2026)

ARDL Estimation Results

Table 9. ARDL Estimation Results

Dependent Variable: LNCE			
Variables	Model 1 Baseline	Model 2 Digitalization	Model 3 Interaction
Long-run Estimates			
FD	-0.048994	-0.001580	
FEC	0.086422	0.006235	
REC	0.048184	--0.042971*	
LNDI		-0.004328	
FD*LNDI			-0.000150
FEC*LNDI			0.001603*
REC*LNDI			-0.001012*
PCI	-0.026352***	-0.009984*	-0.002083
Constant	-3.161715	8.060130*	4.740951*
Error Correction			
ECM(-1)	-0.411421*	-0.958877*	-0.940289*
Speed of Adjustment	41.14%	95.89%	94.03%
Short-run Estimates			
Δ LNCE(-1)	-0.540336*		0.156880
Δ LNCE(-2)	-0.346586*		-0.239474*
Δ FD	-0.015336*		
Δ FD(-1)	0.016073*		
Δ FD(-2)	0.017125*		
Δ FD(-3)	-0.006918*		
Δ FEC	0.019207*		
Δ FEC(-1)	-0.016353*		
Δ REC	-0.040664*		
Δ REC(-1)	-0.048607*		
Δ REC(-2)	0.017745*		
Δ REC(-3)	0.033743*		
Δ LNDI		-0.011980*	
Δ LNDI(-1)		-0.006553*	
Δ (FEC*LNDI)			0.000868*
Δ (FEC*LNDI(-1))			-0.000637*

$\Delta(\text{REC}*\text{LNDI})$			-0.000699*
$\Delta(\text{REC}*\text{LNDI}(-1))$			0.000276*
$\Delta(\text{REC}*\text{LNDI}(-2))$			-5.58E-05***
ΔPCI	-0.012770*	-0.001106	0.001764
$\Delta\text{PCI}(-1)$	-0.003899**	0.006502*	0.008611*
$\Delta\text{PCI}(-2)$	0.007941*	0.003975**	0.004454*
$\Delta\text{PCI}(-3)$	0.004812*		
Model Statistics			
R-squared	0.983379	0.912148	0.900129
Adjusted R-squared	0.962922	0.894578	0.850193
F-statistic	48.07107*	51.91414*	18.02575*
Durbin-Watson	2.381653	1.930248	2.245200

Source: Authors' Computation from Estimations using EViews (2026)

Note. () signifies 1% level of significance, (**) signifies 5% level of significance, and (***) signifies 10% level of significance.

The long-run and short-run ARDL results for the three estimated models are presented (see Table 9). In the long run, financial development, fossil fuel energy consumption, and digitalization are not statistically significant across the models. Renewable energy consumption becomes negative and statistically significant in Model 2 only. While economic growth is negative and statistically significant in Models 1 and 2, and insignificant in the interaction model. In the interaction model, the financial development-digitalization interaction is negative and statistically insignificant. Whereas fossil fuel energy consumption-digitalization and renewable energy consumption-digitalization interactions are statistically significant, being positive and negative respectively.

The estimated error correction terms are negative, less than 1, and statistically significant at the 1% level across all models, confirming the existence of stable long-run relationships among the variables. The short-run estimates display dynamic and significant effects among the dependent variable and its explanatory variables.

The diagnostic statistics indicate that the estimated models provide satisfactory fit, with high explanatory powers, and are free from serious autocorrelation in the residuals.

4.2 Discussion of the Findings

The ARDL estimates indicate that carbon emissions are jointly influenced by financial development, energy consumption, digitalization, and economic growth in Nigeria (see Table 9). The sequential modelling strategy demonstrates that the incorporation of digitalization alters the channels via which finance and energy affect environmental sustainability. Confirming digital transformation as an integral conditioning mechanism in the finance-energy-environment nexus. This finding is supported by Ke et al. (2022), Le and Pham (2024), Udo et al. (2025), and Zhang and Wang (2023). In Nigeria, with rapid digital expansion, environmental outcomes are better explained by the interrelationship between the financial systems, energy composition, and technological progress, rather than in isolation.

The negative, less than 1, and statistically significant error correction terms confirm stable long-run equilibrium in the models. The speed of adjustment substantially increases after digitalization is incorporated, implying that digital transformation facilitates the flow of information and decreases costs of adjustment, thereby enabling faster adaptation to shocks. Reflecting Nigeria's rapid growth in digital technologies, which improve financial transactions and information dissemination across the economy. Indicating that the resilience of Nigeria's finance-energy-environment system is strengthened by

digitalization. Similar evidence is reported by Ke et al. (2022) and Zhang and Wang (2023) in emerging economies undergoing digital transformation.

Financial development and emissions display a dynamic relationship, reflecting the structure of Nigeria's bank-dominated financial system. Greater access to credit in the short run enables firms to replace obsolete inputs with more energy-efficient technologies, thereby reducing emissions. However, continuous credit expansion is redirected towards sectors and activities that are predominantly dependent on fossil fuel. The long-run effect is statistically insignificant, suggesting that financial deepening alone cannot improve environmental outcomes in the face of limited green financing. This finding is in line with Acheampong (2019), Mahalik et al. (2017), and Tamazian et al. (2009), who argue that financial resource allocation is more important than financial depth itself. Thus, emphasizing that in Nigeria, bank credit expansion in the absence of effective green financial intermediation is unlikely to deliver sustained emission reductions.

Energy composition remains the primary mechanism that determines emissions; this is because Nigeria's electricity generation and industrial production are predominantly fossil fuel dependent. Frequent electricity outages have compelled economic agents to rely extensively on fossil fuel-powered generators. This finding is in agreement with Usman et al. (2021), who argue that fossil fuel energy combustion is the predominant source of greenhouse gas emissions in developing economies. Conversely, renewable energy limits emissions, with the incorporation of digitalization improving the environmental benefits. Hence, suggesting that digital technologies improve renewable energy integration via smart metering and monitoring, alongside efficient electricity management. Similarly reported by Anton and Afloarei Nucu (2020), Lahiani et al. (2021), Wang et al. (2025), and Yu et al. (2022, 2023).

Digitalization displays a developmental paradox in Nigeria. Despite digital expansion improving production efficiency, lowering transaction costs, and facilitating technological diffusion while reducing emissions, over time, Nigeria's digital infrastructure dependence on fossil fuel-based electricity generation erodes these gains, thereby stimulating emissions. The rapid growth of telecommunications networks, data centres, and digital platforms has substantially led to increased electricity demand, which is mainly facilitated via fossil fuel-powered generators owing to persistent grid instability. This finding is in alignment with the digitalization paradox by Ke et al. (2022), and consistent with Onyeneke et al. (2024), who found that the predominant energy mix determines the environmental benefits of digitalization.

Evidence exhibited by economic growth reflects that higher income levels are associated with lower emissions over time. Suggesting gradual structural transformation towards cleaner production. Although the effect is modest, indicating that Nigeria is yet to commit fully to its environmentally sustainable growth transition; as a result, environmental improvements are hindered by the continuous fossil fuel dependence. This finding is in line with Acheampong (2019).

Moderating Role of Digitalization in the Finance-Energy-Environment Nexus

The interaction model provides the primary contribution, indicating digitalization moderates the environmental effects of the finance-energy nexus, rather than acting solely as a direct determinant of emissions. The conventional finance-energy-environment nexus is extended by this finding, supporting Ke et al. (2022) and Le and Pham (2024), who argue that production systems, financial intermediation, and energy utilization are simultaneously reshaped by digital transformation.

The positive interaction between fossil fuel consumption and digitalization indicates that expansion in digital technologies amplifies the environmental cost of fossil fuel use. In Nigeria, the expansion of telecommunications infrastructure, fintech, cloud services, and digital services has led to increased

electricity demand supplied primarily via gas-powered and diesel-powered generators due to unreliable grid power. This finding aligns with the rebound effect by Ke et al. (2022), also in line with Onyeneke et al. (2024). Contrarily, the interaction between renewable energy consumption and digitalization is negative and statistically significant. Suggesting that the environmental benefits of renewable energy are amplified by digital transformation via smarter energy management, digital monitoring, and improved system efficiency, corroborating the findings of Le and Pham (2024), Wang et al. (2025), and Yu et al. (2022, 2023).

The interaction between financial development and digitalization is negative and statistically insignificant. Demonstrating that Nigeria's digital financial innovation has not fundamentally redirected financial resources towards environmentally sustainable investments. While fintech has improved financial inclusion and the efficiency of payments, green finance remains underdeveloped, with credit continuously flowing to the conventional sectors. This finding is supported by Asongu and Odhiambo (2023), Ma et al. (2022), and Svirydenka (2016).

Digitalization is neither inherently environmentally beneficial nor harmful based on evidence from the findings. The predominant energy structure and financial intermediation quality determine its environmental impact. Where digital infrastructures are fossil fuel-driven, it promotes emissions. When digital technologies are driven by renewable energy, it hinders emissions. Conflicting evidence in the existing literature is reconciled by the findings of this study. Thus, integrating renewable energy expansion, green finance, and sustainable digital infrastructure presents the most effective pathway towards achieving a low-carbon transition in Nigeria, in line with Dimian et al. (2025) and Zhang et al. (2026).

5. Conclusion and Recommendations

5.1 Conclusion

The relationship between financial development, energy consumption, digitalization, and carbon emissions in Nigeria covering the period 1990 to 2023 is examined in this study. Employing the ARDL framework, the study distinguished between fossil fuel and renewable energy consumption, while modelling digitalization as both an explanatory and moderating variable. Thus, a more robust understanding of the finance-energy-environment nexus in a resource-rich, fossil fuel-dependent economy is provided.

Evidence of mixed environmental effects of financial development is revealed by the findings. In the short run, financial expansion reduces emissions via improved resource allocation and efficient investment. Its long-run effect is statistically insignificant, demonstrating that the financial system in Nigeria is currently ineffective in facilitating prolonged environmentally sustainable investment. Fossil fuel consumption remains the primary driver of emissions in Nigeria, with renewable energy consumption contributing to improvements in the environment. Emissions are initially reduced by digitalization as it generates short-run efficiency gains, but over time these benefits wear off and weaken due to Nigeria's fossil fuel electricity-based digital expansion. Consequently, digitalization strengthens the emissions-limiting effect of renewable energy, while amplifying the environmental degradation associated with fossil fuel consumption. This indicates that the energy source driving digitalization has significant environmental impacts.

By incorporating digitalization as a moderating mechanism, this study contributes to the existing literature by extending the conventional finance-energy-environment framework. Thus, generating evidence to illustrate that digital technologies are neither inherently environmentally beneficial nor harmful. Rather, the energy system and financial resources allocation determine the environmental

effects. This integrated perspective helps reconcile conflicting evidence in the literature. Likewise, underlining the significance of examining the finance-energy-digitalization nexus as an interconnected system.

This study has some limitations despite its contributions. Measurement issues arise as digitalization and financial development are proxied by mobile cellular subscriptions and domestic credit to the private sector, respectively, which may not fully capture their multidimensional nature. Likewise, the renewable energy indicator has traditional biomass included in its composition, limiting the distinction between modern renewable technologies and conventional biomass. Future studies should employ broader indicators of digitalization and financial development and likewise distinguish modern renewable energy sources from traditional biomass. These studies should also employ advanced econometric techniques to explore potential nonlinear relationships, and comparatively extend the analysis across other developing economies.

Nigeria's transition to a low-carbon economy is not dependent on isolated improvements in finance, energy, or digitalization, but on their effective integration, as evidenced by the study. Environmental sustainability can either be accelerated or hindered by digital transformation depending on the energy systems and financial institutions that power and finance it, respectively. The most credible pathway for Nigeria to achieve its climate and sustainable development goals is through a coordinated strategy linking green finance, clean energy, and sustainable digital infrastructure.

5.2 Recommendations

Based on these findings, the following policy recommendations are proposed for Nigeria:

- a) The Central Bank of Nigeria, Bank of Industry, Federal Ministry of Finance, Nigerian Communications Commission (NCC), and National Information Technology Development Agency (NITDA) should collaborate to promote green digital transformation by directing financial resources toward renewable energy projects, energy-efficient industrialization, and sustainable digital infrastructure. This should be supported through green financing instruments, fiscal incentives such as tax relief and reduced import duties for clean technologies, and policies that ensure digital investments, including broadband networks, data centres, fintech services, and artificial intelligence applications, are powered by renewable energy to minimize the environmental footprint of digital expansion.
- b) The Federal Ministry of Power, Rural Electrification Agency (REA), and National Council on Climate Change (NCCC) should prioritize investments in decentralized renewable energy infrastructure, including smart grids, renewable-powered mini-grids, digital metering, and automated energy management systems, particularly in underserved rural communities that rely heavily on fossil-fuel-based electricity generation. Furthermore, the NCCC should strengthen digital environmental monitoring through smart sensors, satellite-based technologies, and enhanced inter-agency coordination with finance, energy, and technology regulators to improve emissions reporting, regulatory compliance, and the achievement of Nigeria's climate and green growth objectives.

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