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Exploring the N-Shaped Nexus between Financial Inclusion and Environmental Management in Nigeria: Evidence from the STIRPAT and DARDL Framework

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This study assesses the interplay between digital financial inclusion (DFI) and environmental sustainability (ENV) in Nigeria, considering the role of industrialization (IND), urbanization (URB), and energy consumption (EC). While DFI enhances financial access and green investments, its environmental impact remains uncertain. Extant studies predominately use indirect proxies, ignoring the direct indicators that capture its breadth and depth. Adopting the direct DFI indicators: mobile money accounts per capita (NMM), mobile money transactions (MMT), active digital accounts (ADA), and volume of mobile transactions (VMM). The study investigates whether DFI fosters ENV through renewable energy (REN) adoption or contributes to ENV degradation through increased energy consumption (EC). Using the Dynamic Autoregressive Distributed Lag model within the extended STIRPAT framework. Results confirm an N-shaped Environmental Kuznets Curve (EKC), where inclusive economic growth (IEG) initially degrades ENV (0.362 to 0.843), improves at higher income levels (-0.559 to -0.912) but rebounds again at very high incomes (0.341 to 0.592). IND reduces emissions (-0.518 to -0.682) except for VMM (0.112), indicating the environmental costs of DFI infrastructure. Trade openness (TOP) initially increases emissions (0.230) but lowers them in the long term (-0.536 to -0.741). Foreign direct investment (FDI) reduces emissions (-0.210 to -0.619), while REN initially decreases ENV (0.820) but improves ENV in the long term (-0.901). Error correction terms (-0.833 to -0.922) confirm rapid convergence to equilibrium. Policy recommendations include strengthening green financial regulations, promoting energy-efficient digital infrastructure, balancing TOP with ENV protection, and accelerating clean energy transitions to ensure sustainable IEG .

Keywords: CO2 emissions, digital financial inclusion, classical financial inclusion, environmental sustainability, Nigeria, STIRPAT, EKC,

Balancing economic inclusivity with environmental sustainability (ENV) remains a strategic challenge and goal for both emerging and developed economies. In emerging markets like Nigeria, the realization of this goal is particularly challenging due to the heavily dependent on carbon-intensive industries, and over-prioritization of inclusive economic growth (IEG) without concern for ENV often leads to ENV degradation. The lax enforcement of ENV regulations, coupled with insufficient financial capacity to invest in sustainable infrastructure, further exacerbates the challenge. Nigeria's development model presents a dilemma between promoting IEG and sustaining ENV.

Financial inclusion (FI), encompassing both traditional (TFI) and digital (DFI) approaches, has been globally acknowledged as a pivotal driver of IEG. By expanding access to financial services, FI empowers individuals, households, and businesses to save, invest, and engage in productive economic activities (Udo et al., 2023; Samuel et al., 2023; Samuel et al., 2018). While DFI, enabled by mobile and internet technologies, enhances access to financial services, TFI, facilitated by physical branches, ATMs, and paper-based banking, remains essential in some regions. Thus, leading to a geometric increase in FI from 24% in 2008 to 64% in 2023, demonstrating the growing role of DFI in economic transformation. However, its environmental impact remains ambiguous.

DFI facilitates investments in renewable energy (REN), promotes eco-friendly consumption, and green entrepreneurship, and reduces reliance on cash-based transactions. It also mitigates financial exclusion stemming from

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poverty, income inequality, and systemic market failures and enables sustainable industrialization (IND) and urbanization (URB) by enhancing financial literacy and supporting green projects such as REN adoption and carbon credit trading (Udoh et al., 2024; Inim et al., 2024). However, despite DFI and TFI's significant contribution to FI and IEG, it also poses significant environmental risks.

The environmental impact of FI especially through DFI channels has becomes a growing concern. As such the proliferation of energy-intensive infrastructure such as data centers, mobile networks, and digital platforms exacerbates CO_2 emissions and e-waste accumulation. The International Energy Agency (IEA) reports that data centers account for 1% of global electricity demand, with potential increases as DFI expands. Additionally, Bitcoin mining alone generates over 22 megatons of CO_2 emissions annually (Onat et al., 2025). The rapid expansion of 5G networks in emerging economies, required to support DFI, further increases energy consumption (EC) through the proliferation of connected devices.

Nigeria's lack of adequate e-waste recycling infrastructure further degrades ENV, as millions of discarded digital devices such as digital kiosks, point-of-sale (POS) systems, ATMs, and mobile phones contribute to landfill pollution. The Global E-Waste Monitor 2020 report revealed that only 17.4% of the 53.6 million metric tons of global e-waste is properly recycled. The environmental costs associated with maintaining physical banking network infrastructures contribute to ENV degradation, as such the Agricultural Bank of China, reported emitting CO_2 emissions exceeding two million tonnes in 2022. The growing concern associated with DFI is that, while it enhances access to sustainable investments, its environmental costs may outweigh the benefits in Nigeria, like other emerging economies, already grappling with rapid IND, URB, and a growing reliance on fossil fuels. These concerns raise a critical question: can DFI effectively balance IEG with ENV, or does its environmental footprint undermine its economic benefits?

To assess this question, this study employs the Environmental Kuznets Curve (EKC) hypothesis, which posits that the IEG-ENV nexus follows an inverted U-shape. Initially, IEG and IND increase ENV degradation. However, as the economy evolves beyond a certain income threshold, ENV is prioritized as an increase in income level enables a shift toward more sustainable practices and the adoption of stringent ENV regulations (Inim et al., 2024; Udo et al., 2024; Wang et al., 2024; Balsalobre-Lorente et al., 2021).

However, contemporary literature proposed an alternative N-shaped curve, where ENV degradation resurges at very high-income levels due to higher consumption and scale effects (Shaheen et al., 2022; Gyamfi et al., 2021). This alternative trajectory challenges the traditional EKC model and raises concerns about whether Nigeria's rising DFI adoption will follow an inverted U-shaped or N-shaped pattern. Additionally, this study explores two competing hypotheses within the trade (TOP) and investment framework: The Pollution Haven Hypothesis (PHH) posits that emerging economies with lax ENV regulations attract pollution-intensive foreign direct investment (FDI), which deteriorate ENV (Emmanuel et al., 2023). As a result, DFI-facilitated TOP could degrade ENV unless strict ENV regulations are enforced. Pollution Halo Hypothesis (PH) argues that FDI can improve ENV through the adoption of cleaner technologies, promoting energy-efficient industries (Zaidi et al., 2021), and adopting DFI direct channels such as mobile money accounts per capita (NMM), mobile money transactions (MMT), active digital accounts (ADA), and volume of mobile transactions (VMM) to enhance sustainable growth through financial access to green investments.

Studies empirically assess how DFI adoption directly influences ENV outcomes in Nigeria. Using the DFI indirect indicators such as mobile network coverage and broadband access (Ruba, 2023; Nur Yuliany et al., 2021), these studies ignored the direct measures of DFI's impact on the environment. This gap spurs the need for more precise metrics like the NMM, VMM, MMT, and ADA, to capture DFI access, usage, and penetrations that directly impact both IEG and ENV. This study explores whether Nigeria's rising DFI adoption follows the inverted U-shaped or N-shaped pattern, and also examines its dual impacts on IEG and ENV to provide insights into the complex interplay between DFI and ENV.

This study also explores the potential synergy between DFI and REN. The integration of REN into DFI infrastructure presents a direct pathway for reducing the environmental burden of DFI and simultaneously supporting IEG. Studies by Abner et al., (2021); Udo et al., 2024; and Udoh et al., (2024) reveal that transitioning from fossil fuels to cleaner energy sources such as solar and wind power can mitigate the EC associated with DFI and enhance the sustainability of FI efforts.

Given these theoretical foundations, this study aims to:

1. Assess the direct effects of DFI indicators on ENV in Nigeria.
2. Investigate how population, affluence, and technology influence the DFI, REN, and ENS nexus.
3. Test whether Nigeria's DFI-driven growth follows an inverted U-shape or N-shape EKC trajectory, and determine whether DFI can effectively balance IEG and ENV.

This study contributes to the literature by directly quantifying the environmental impact of DFI, an area largely ignored in previous studies. By adopting NMM, VMM, MMT, and ADA as direct measures of DFI usage, access, and penetration, this study offers more granular insights compared to previous studies relying on indirect proxies.

By employing the Dynamic Autoregressive Distributed Lag (DARDL) model within the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework. The STIRPAT model decomposes ENV drivers into population, affluence, technology, and additional factors like URB, DFI, and REN, providing a comprehensive perspective on the complex dynamics between IEG, DFI, and ENV.

By integrating the EKC hypothesis, PHH, and PH, this study provides a multi-dimensional assessment of whether DFI supports both IEG and ENV in Nigeria, offering valuable policy insights for achieving sustainable financial and environmental goals.

Literature Review

FI and ENV Link

DFI enhances ENV by promoting access to financial services that support cleaner technologies, reduce cash-based transactions, and lower carbon emissions (Samuel et al., 2023; Wan et al., 2021; Inim et al., 2024). Studies reveal that DFI accelerates REN adoption and green technologies, improving ENV in diverse contexts (Zaidi et al., 2021; Udo et al., 2024). In OECD countries, DFI facilitated REN adoption by enhancing financial accessibility (Zaidi et al., 2021). Udo et al., (2024) further revealed that DFI accelerates green technology adoption to improve ENV. Additionally, Sun et al., (2022) noted that fintech-driven green credit promotes eco-friendly businesses, yet cautioned that unregulated digital transactions could increase EC and carbon footprints, particularly in emerging economies. Despite these benefits, the rapid expansion of DFI introduces environmental risks through increased EC and e-waste from data centers, blockchain, and digital platforms. These technological infrastructures create an environmental burden, potentially offsetting DFI’s environmental advantages. However, Inim et al., (2023) recommend that effective regulatory frameworks can help align DFI with climate policies.

Similarly, TFI characterized by brick-and-mortar banking, degrades ENV. Expansions in physical banking infrastructure, such as bank branches, ATM galleries, and financial centers, increase EC, contributing negatively to ENV (Wan et al., 2021). Amin et al., (2022) attributed TFI's adverse environmental impacts to lax environmental policies and unregulated credit expansion. Other studies (Udoh et al, 2024; Le et al., 2020; Ali et al., 2019; Ahmad et al., 2022) linked TFI's negative environmental impact to resource overexploitation and limited environmental awareness.

Non-linear DFI-ENV Nexus: Revisiting the EKC Hypothesis

Studies exploring the EKC hypothesis propose a non-linear DFI-ENV nexus with varied perspectives. Qin et al., (2021), Hung et al., (2018), and Renzhi and Baek (2020) observed an inverted U-shaped nexus between financial development and ENV, where financial development initially degrades ENV before improvement occurs beyond a certain financial development threshold. Expanding these insights, Grossman and Krueger (1995) proposed that the DFI-ENV nexus could follow an N-shaped trajectory, where DFI initially enhances ENV, then deteriorates it, and stabilizes it at a higher level of financial development. Sun et al., (2022), in supporting this N-shaped pattern, emphasized its under-exploration in emerging economies, underscoring the need for country-specific analyses. Addressing this gap, this study investigates whether DFI in Nigeria follows an N-shaped trajectory, providing insights into how DFI influences ENV amidst high financial exclusion and fossil fuel dependence. The study hypothesizes:

H_1: There is an N-shaped nexus between DFI and ENV in Nigeria.

To assess DFI’s influence on ENV, this study integrates the Solow-Swan growth model, which emphasizes capital, labour, and technology in sustainable growth, and the STIRPAT model, which assesses the impacts of population, affluence, and technology on ENV. By incorporating DFI and REN adoption, this approach provides a comprehensive analysis of the DFI-ENV nexus, bridging gaps in existing research.

Research Gap and Contribution

Despite growing interest in the DFI-ENV nexus, key gaps remain:

1. Limited focus on the N-shaped DFI-ENV nexus: Most studies explore the linear or inverted U-shaped links, neglecting the potential N-shaped nexus, especially in emerging economies.

2. Underrepresentation of direct DFI indicators: Extant studies predominantly used indirect indicators such as financial depth and access, which do not accurately capture DFI's operational intensity.
3. Methodological limitations**:** Extant studies by (Zaidi et al., 2021; Zhao et al., 2021) relied on cross-sectional or static models, which cannot capture evolving DFI-ENV dynamics over time.

This study addresses these gaps by employing the DARDL model to capture the short- and long-run dynamics of DFI-ENV interactions in Nigeria. Using direct DFI indicators such as NMM, and VMM. ADA and MMT. By integrating STIRPAT and Solow-Swan models, the study offers a robust analysis, advancing the understanding of DFI's environmental role and informing policy frameworks that support sustainable development.

Theoretical Framework

EKC and STIRPAT Models:

The EKC framework proposed by Grossman and Krueger (1995) proposes an inverted U-shaped link between IEG and ENV, where IEG is driven by IND degrades ENV due to material output prioritization and lax ENV regulations, but higher income levels, combined with robust ENV regulatory frameworks, shift economies toward cleaner technologies, enhancing ENV. Despite the EKC heuristic value, the hypothesis is heavily criticized for oversimplification, assuming a uniform path for all countries, and ignoring institutional, regional, and sectoral differences. It also ignores factors such as energy sources, technology innovation, and regulatory quality, which significantly influence ENV outcomes. Given Nigeria's reliance on fossil fuels, limited financial access, and lax regulatory frameworks, the DFI-ENV trajectory may deviate from EKC's U-shape pattern, and potentially follow an N-shaped pattern, due to persistent structural constraints, rising energy demands from DFI infrastructure, before potentially stabilizing with sustainable policies.

To address EKC's limitations, the STIRPAT model proposed by Dietz and Rosa, (1994) refines the deterministic and non-stochastic nature of IPAT ($Impact = Population \times Affluence \times Technology$) which ignores variations over time and across contexts. The STIRPAT model introduces stochastic elements, allowing for empirical flexibility and the assessment of non-linear DFI-ENV nexus, including potential N-shaped patterns.

The STIRPAT model: $I = a_{it}P^{b1} \times A_{it}^{c2} \times T_{it}^{d3} \times \varepsilon_{it} \dots \dots \dots \dots \dots \dots (1)$

To facilitate analysis using the DARDL model, the STIRPAT equation is transformed into a log-linear form:

$$InI = Ina + b_1 InP + c_2 InA + d_3 InT + \varepsilon \dots \dots \dots \dots \dots \dots (2)$$

Where: I = environmental impact, P = population, A = affluence (PGDP), T = technology, and ε = error term.

This study extends the STIRPAT model by incorporating DFI metrics, along with REN, URB, IND, EC, FDI, and TOP. This approach assesses Nigeria's ENV dynamics, evaluating EKC validity while addressing its limitations.

Table 1
Digital Financial Inclusion Indicators

Indicators	Measures	Justification
Mobile money accounts per capita (NMM)	Access	Reflects financial access by showing how many people can use formal services via mobile. Indicates true financial inclusion.
Volume of mobile money transactions (VMM)	Usage	Reflects active service use and economic integration, signifying both FI and digital payment adoption.
Active digital accounts (ADA)	Penetration and Usage	Shows sustained use of financial services beyond account ownership, indicating effective financial inclusion.
Mobile money transactions (MMT)		Reflects a mature ecosystem, indicating both FI and broader economic participation.

Source; Authors (2024)

Data and Methodology

This study examines the DFI-ENV nexus in Nigeria from 1999 to 2023, using the DARDL model within the STIRPAT framework to capture both short- and long-term dynamics. Data sources are presented in Table 2.

Table 2

Variable Descriptions and Units.

Variables	Indicators	Justifications	Expected Sign
Carbon Footprint (CO_2emissions)	Environmental Sustainability (ENV)	Measures environmental degradation.	Dependent Variable
Urbanization (URB)	Urban Population	Has dual effects: enhances energy efficiency but may increase emissions due to increasing energy demand (Zhao et al., 2019).	+/−
Industrialization (IND)	Manufacturing, value added (% of GDP)	Boosts growth but increases emissions unless green technologies are adopted. (Udoh et al., 2024).	+/−
GDP per capita (constant $ 2015) (PGDP)	Inclusive Growth	It captures economic growth's impact on ENV, reflecting EKC dynamics, population effects, and sustainability transitions through green policies and technology adoption.	+
Trade Openness (TOP)	Trade (% of GDP)	Expands industrial output and emissions via trade-related activities.	+
Foreign Direct Investment (FDI)	Net inflow (% of GDP)	Promotes green tech transfer.	-
Energy Consumption (EC)	Fossil fuel energy consumption (% of total energy)	A major source of CO2 emissions.	+
Renewable Energy (REN)	Renewable energy consumption (% of total final energy consumption)	Lowers fossil fuel reliance.	-
Mobile money accounts per capita (NMM)	Digital Financial Inclusion Strategies (DFI)		+/−
Volume of mobile money transactions (VMM)			-
Active digital accounts (ADA)			+/−
Mobile money transactions (MMT)			+/−

Source: Author's Compilation (2024)

EKC Model Specification

The EKC hypothesis is tested using the following equation:

$$CO_2 = \beta_0 + \beta_1 IEG + \beta_2 IEG^2 + \beta_3 IEG^3 + X + \varepsilon \ldots\ldots\ldots\ldots..(5)$$

Where: PGDP = GDP per capita, reflecting income levels and X = control variables influencing ENV.

EKC Interpretation:

$\beta_1 > 0 =$ higher IEG initially increases CO_2 emissions.

$\beta_2 < 0 =$ At higher income levels, CO_2 emissions decline as cleaner industries and green policies take effect.

$\beta_3 > 0 =$ a rebound in emissions after a certain threshold, due to increased IND, URB, EC, from IEG, and the environmental costs of DFI. The turning point (IEG*) is calculated as IEG* $= -\frac{\beta 1}{2\beta 2}$.

DARDL Model Application

The DARDL model captures both short- and long-run dynamics, addressing potential structural breaks in Nigeria's financial and environmental landscape. Unlike the ARDL, it accommodates evolving DFI-ENV interactions and mixed orders of variables integration (I(0) and I(1)). Compared to FMOLS and VECM, DARDL flexibility is crucial for analysing Nigeria's dynamic economic environment, where shifts in policy, technology adoption, and market conditions significantly influence the DFI-ENV nexus.

H_0: Digital Financial Inclusion (FI_{digit}) on Environmental Sustainability.

$$\Delta CO_{2t} + \propto_0 + \sum_{j=1}^{p} \propto_i \Delta CO_2 + \sum_{j=1}^{k1} \propto_1 \Delta DFI_{t-1} + \sum_{j=1}^{k2} \propto_2 \Delta REN_{t-1} + \sum_{j=1}^{k3} \propto_3 \Delta IND_{t-1} + \sum_{j=1}^{k4} \propto_4 \Delta EC_{t-1}$$
$$+ \sum_{j=1}^{k5} \propto_5 \Delta FDI_{t-1} + \sum_{j=1}^{k6} \propto_6 \Delta TOP_{t-1} + \sum_{j=1}^{k7} \propto_7 \Delta IEG_{t-1} + \sum_{j=1}^{k8} \propto_8 \Delta IEG^2{}_{t-1} + \sum_{j=1}^{k9} \propto_9 \Delta IEG^3{}_{t-1}$$
$$+ \sum_{j=1}^{k10} \propto_{10} \Delta URB_{t-1} + \delta_1 CO_{2t-1} + \delta_2 FDI_{digit_{t-1}} + \delta_3 REN_{t-1} + \delta_4 URB_{t-1} + \delta_5 IND_{t-1}$$
$$+ \delta_6 FDI_{t-1} + \delta_7 TOP_{t-1} + \delta_8 \Delta IEG^2{}_{t-1} + \delta_9 \Delta IEG^3{}_{t-1} + \delta_{10} IEG_{t-1} + \varepsilon_{it} \ldots\ldots\ldots (6)$$

ECM specification

$$\Delta CO_{2t} + \phi_0 + \sum_{j=1}^{k} \phi_1 \Delta CO2_2 + \sum_{j=1}^{k} \phi_1 \Delta DFI_{t-1} + \sum_{j=1}^{k} \phi_2 \Delta REN_{t-1} + \sum_{j=1}^{k} \phi_3 \Delta IND_{t-1} + \sum_{j=1}^{k} \phi_4 \Delta EC_{t-1}$$
$$+ \sum_{j=1}^{k} \phi_5 \Delta FDI_{t-1} + \sum_{j=1}^{k} \phi_6 \Delta TOP_{t-1} + \sum_{j=1}^{k} \phi_7 \Delta IEG_{t-1} + \sum_{j=1}^{k8} \propto_8 \Delta IEG^2{}_{t-1} + \sum_{j=1}^{k9} \propto_9 \Delta IEG^3{}_{t-1}$$
$$+ \sum_{j=1}^{k10} \propto_{10} \Delta URB_{t-1} + \gamma_1 ECM_{t-1} + \varepsilon_{it} \ldots\ldots\ldots (6b)$$

where $\propto_1 - \propto_{10}$; $\infty_1 - \infty_2$ and $\delta_1 - \delta_{10}; \varphi_1 - \varphi_{10}$ =regression coefficients; $\propto_0 - \infty_0$ =constant; ε_{it} = error term; ECM_{t-1}=lagged error term; and (γ_1) = speed of convergence from short-run shocks to long-run equilibrium (negative and significant). The diagnostic test results consisted of autoregressive conditional heteroscedasticity (ARCH), the Breusch–Godfrey (BG) test for serial correlation, and the Jarque–Bera (JB) test for normality. A bound test was conducted to assess the presence of a long-run link among the series.

Unit Root Test and Co-integration Tests

The stationarity of the series was tested using the Augmented Dickey-Fuller (ADF) test and the Zivot and Andrews (1992) test to account for structural breaks not captured by the ADF, the results are presented in Table 4 (Panels A, B, and C). The Bound test results confirmed long-run nexus if the *F*-statistics is (>) the upper critical value at a 5% level of significance. The series was also assessed for potential multicollinearity issues and model selection relied on the Akaike Information Criterion (AIC) the lower value of AIC was the selected result (Table 5).

Results and Discussions

Table 3

Descriptive Statistics

	Mean	Std. Dev.	Skewness	Kurtosis
CO2	2.45	0.72	0.58	2.91
EC	60.23	15.34	0.75	3.12
NMM	18.45	5.67	0.48	2.87
VMM	12.78	4.89	0.62	2.95
ADA	10.34	3.45	0.54	3.01
MMT	8.56	2.98	0.67	2.83
FDI	4.12	1.34	0.71	3.15
IEG	3500.45	950.23	0.63	2.89
IND	24.78	7.89	0.59	2.92
REN	15.67	5.12	0.55	2.88
TOP	45.34	12.45	0.7	3.1
URB	35.67	10.23	0.66	2.96

Source: Author's (2024)

The results in Table 3 highlight an N-shaped relationship between DFI and ENV in Nigeria, analyzed through the STIRPAT and DARDL models. The mean CO_2 emissions (2.45) and standard deviation (0.72) suggest stable yet significant environmental degradation. Positive skewness (0.58) indicates occasional spikes, mainly due to fossil fuel reliance and industrial activities. A kurtosis value of 2.91 suggests a near-normal distribution, reinforcing the need for integrating REN and regulating EC in financial inclusion strategies. Nigeria's high energy consumption (mean: 60.23) reflects a strong dependence on fossil fuels, with positive skewness (0.75) and kurtosis (3.12) showing demand spikes linked to industrialization and urbanization. Policies promoting REN are essential to balance DFI growth with environmental sustainability. DFI indicators (NMM: 18.45, VMM: 12.78, ADA: 10.34, MMT: 8.56) indicate growing but uneven financial inclusion. Positive skewness (0.48–0.67) and kurtosis (2.83–3.01) suggest normal distribution.

However, the gap between access (NMM) and usage (MMT) implies that unless DFI integrates energy-efficient infrastructure, its environmental impact may follow an N-shaped trajectory. Macroeconomic indicators (IEG: 3500.45, IND: 24.78, TOP: 45.34, URB: 35.67) suggest economic growth but with environmental trade-offs. Limited REN adoption (mean: 15.67) underscores the need for green financing to align DFI expansion with sustainability.

Unit Root and Multicollinearity Tests

The ADF test results in (Table 4, Panel A) confirm stationarity at I(0) and I(1), but not I(2) justifying the use of the DARDL model, in analysing the DFI-ENV nexus. To enhance robustness, the Zivot and Andrews test results (Panel B) further validate stationarity while identifying structural breaks aligning with key financial and energy reforms in Nigeria, including banking consolidation (2004–2005), mobile banking adoption (2009–2012), fintech expansion (2015–2023), and renewable energy policies (2017–2023). The VIF test (Panel C) confirms no multicollinearity (all values <10), ensuring robust estimations. These results highlight DFI's role in FI, reducing carbon reliance, and promoting ENV.

Table 4

Augmented Dickey-Fuller (ADF) Unit Root Test Results

	ADF-Stat	**Critical Values 5%**	**Order of Integration**	**ZAU Stat**	**Critical Value (%5)**	**Break Date**	**Order of Integration**	**Multicollinearity**
	Panel A: Trend and Intercept				**Panel B: Trend and Intercept**			**Panel C: VIF**
CO2	-5.563	-2.345	I(1)	-7.52	-5.08	2016	I(1)	5.112
EC	-6.012	-3.812	I(0)	-6.78	-4.50	2017	I(1)	5.362
NMM	-5.231	-2.301	I(1)	-5.93	-4.36	2015	I(1)	5.240
VMM	-6.562	-3.510	I(0)	-4.93	-2.50	2022	I(1)	5.221
ADA	-6.431	-2.421	I(0)	-6.90	-3.72	2015	I(1)	5.151
MMT	-6.821	-4.052	I(1)	-6.92	-4.26	2012	I(1)	4.310
FDI	-9.011	-5.010	I(0)	-7.44	-3.62	2020	I(0)	5.713
IEG	-6.101	-4.134	I(1)	-7.03	-2.45	2017	I(1)	6.205
IND	-6.214	-3.452	I(0)	-6.22	-406	2022	I(0)	4.300
REN	-7.145	-3.104	I(1)	-7.21	-4.69	2015	I(1)	5.001
TOP	-7.774	-3.052	I(1)	-7.01	-4.61	2020	I(0)	5.011
URB	-5.201	-3.221	I(0)	-5.50	-3.02	2020	I(1)	4.301

Source: Author's (2024)

Co-integrating Bound Test Results

The bound test results (Tabel 5, Panel A) confirm a long-run nexus, with F-statistic (8.334, 9.312, and 18.091) exceeding the 5% critical bounds, indicating DFI enhances ENV by supporting green investments and REN financing while reducing fossil fuel reliance. On the premise of co-integration, the ECM estimates show a convergence from short-run deviations to long-run equilibrium. Diagnostic test results in (Panel B) confirm model robustness: the BG–LM test (>0.5) indicates no autocorrelation, BPG confirms homoscedasticity, and Ramsey RESET validates correct model specification. While DFI improves ENV long-term, short-term trade-offs arise from infrastructure gaps, digital energy demands, and transitional frictions.

Table 5

Autoregressive Distributed Lag (ARDL) Cointegration Test Results

Variables:	Model	Test Statistics (5%)			Panel B: Diagnostic Tests (p values of the F-statistics)			
DP: CO_2		F-stat	I (0)	I (1)	BG LM	BPG	ARCH Test (I)	Ramsey RESET test
MIU	2,2,2,1,0	8.334	2.730	4.163	0.642	0.440	0.431	1.201
MMT	3,3,3,0,3	9.312			0.500	0.548	0.512	2.111
VMB	3,3,3,3,3	18.091			0.423	0.361	0.600	1.128

Source(s): The author's computation using E.views 13

Table 6

ARDL Long and Short Run Model Estimate

Variables: **DP = CO_2 Emissions**	**Model 1** **NMM**	**Model 2** VMM	**Model 3** ADA	**Model 4** MMT
		Long Run		
IEG	0.362**	0.701**	0.618**	0.843**
IEG^2	-0.782**	-0.782**	-0.559**	-0.912**
IEG^3	0.592 **	0.418 **	0.341 **	0.342**
IND	-0.682**	0.112**	-0.518**	-0.541
URB	-0.7180**	0.680**	-0.614**	-0.664**
TOP	0.230*	-0.536**	-0.718**	-0.741**
FDI	-0.619**	-0.210**	-0.417**	-0.418**
EC	0.602**	0.332**	0.702**	0.699**

REN	0.820**	0.521**	-0.901**	-0.892**
Short Run (ECM)				
CointEq (–1)	-0.910**	-0.833**	-0.922**	-0.912**
IEG	0.545**	0.911**	0.903**	0.844**
IEG^2	-0.880**	-0.544**	-1.036**	-1.063**
IEG^3	0.521 **	0.372 **	0.411 **	0.429**
IND	-0.305**	0.300*	-0.3590**	-0.402**
URB	-0.230	----------	----------	-0.245
TOP	-0.432**	-0.702**	-0.522**	-0.546**
TOP(1)	----------	0.672**	0.602**	0.603**
FDI	--------	0.372	0.607	0.537
EC	0.489*	0.432**	0.742**	0.784**
EC(1)	0.933**	0.802	0.388**	0.473**
REN	0.909**	0.587	0.650	0.621**
REN(1)	0.171**	0.491**	0.770**	0.756**
Other Parameter Estimate				
DW Star	2.00	1.73	1.644	1.568

Source(s): Author's (2024)

Discussion

The results in Table 6 reveal the impacts of various factors on ENV in Nigeria, analysed through four DFI channels: NMM, VMM, ADA, and MMT. This result integrates insights from the EKC hypothesis and the STIRPAT model highlighting DFI's dual role in promoting IEG and affecting ENV.

IEG's positive influence on ENV (0.362 to 0.843) implies industrial expansion and EC initially degrades ENV ($IEC > 0$), aligning with the Grossman and Krueger (1995) EKC hypothesis. IEG^2 negative (-0.559 to -0.912) effect on ENV indicates a turning point where higher income levels improve ENV, thus reflecting a structural shift towards cleaner technologies and more efficient energy use ($IEG^2 < 0$), aligning with the inverted U-shaped EKC hypothesis. IEG^3 positive effect (0.341 to 0.592) confirms the N-shaped nexus (IEG > 0) indicating a resurgence of ENV degradation at very high-income levels due to increased consumption and scale effects, aligning with Shaheen et al., (2022). This implies that IEG alone is insufficient for long-term ENV. Promoting green financing, and eco-friendly policies is essential to leverage the EKC turning point effectively. Incentives for REN and sustainable practices are crucial to mitigate the N-shaped resurgence of emissions. IND's mixed results reveal that less fossil-fuel-dependent industries improve ENV (68.2%, 51.8%, and 54.1%) through NMM, ADA, and MMT. However, VMM's positive impact (11.2%) reveals that energy-intensive sectors relying on digital financial services still contribute to ENV degradation, due to the environmental costs of supporting high transaction volumes, dependent on EC for data centers and digital infrastructure. This highlights the need for energy-efficient digital infrastructure and green industrial policies and also aligns with results by (Inim et al., 2024; Udo et al., 2023; Samuel et al. 2023; Zaidi et al., 2021; Sun et al., 2022). Nigeria's reliance on fossil fuels and limited financial access led to a deviation from the inverted U-shaped EKC pattern, potentially following an N-shaped trajectory reported by (Shaheen et al., 2022). These results reveal that green industrialization policies and investment in energy-efficient technologies are needed to balance industrial growth and ENV. URB's negative impact (-0.614 to -0.718) suggests that DFI-enabled urban investments in clean energy and sustainable infrastructure can improve ENV. However, VMM's positive impact (0.680) reflects urban sprawl and increased EC for digital infrastructure. This implies that the environmental benefits are contingent upon sustainable infrastructure investments and regulatory frameworks to manage the risks associated with DFI expansion (Abner et al., 2021; Zaidi et al., 2021).

TOP's dual effect shows that trade openness initially increases emissions (0.230*) but reduces them in the long run (-0.536** to -0.741**) through technology transfer, aligning with the Pollution Haven Hypothesis (PHH). The PHH posits that TOP may attract carbon-intensive industries to Nigeria due to lax ENV regulations (Emmanuel et al., 2023). While TOP may attract carbon-intensive industries, it also facilitates cleaner production practices, emphasizing the need for environmentally friendly trade policies. FDI's negative impact (-0.210** to -0.619**) supports the Pollution Halo Hypothesis (PH), indicating that FDI enhances ENV by enabling cleaner technology transfers. However, without stringent ENV regulations, FDI could lead to degradation. Policies should focus on green FDI and regulatory frameworks. To balance the dual impact of TOP, it is essential to implement trade policies that incentivize environmentally friendly technologies and practices. EC's positive impact (0.332** to 0.702**) confirms that higher EC increases CO_2 emissions, necessitating a shift to cleaner energy sources.

REN mixed effect on ENV shows that the positive impact Model 1 (0.820**) indicates the initial carbon costs of deploying REN increase emissions. This implies that limited grid infrastructure and financing challenges hinder the large-scale adoption of REN in Nigeria. Long-term adoption reduces emissions (-0.901 to -0.892). DFI through NMM, ADA, and MMT supports REN investments, but VMM's environmental cost (11.2%) suggests the need for energy-efficient digital infrastructure and e-waste recycling policies, aligning with findings by (Udo et al., 2024; Inim et al., 2024, Udoh et al., 2024; Zaidi et al., 2021; Shahbaz et al. 2020).

Short-Run ECM Results

The CointEq (–1) values (-0.910, -0.833, -0.922, and -0.912) are negative and significant, confirming a rapid convergence to long-run equilibrium within 4 to 5 months after an economic or environmental shock. This finding highlights DFI's stabilizing role in economic, and environmental interactions. The confirmation of the N-shaped EKC hypothesis in both the short and long run indicates that Nigeria's current economic and environmental policies are insufficient to sustain long-term emission reductions. IEG^3 implies that without sustained green investments, Nigeria's industrial expansion and energy demand could reverse environmental progress. To counter this, stringent ENV regulations, REN adoption, and circular economy practices are necessary. IND mixed results, (-0.305 to -0.402, positive in VMM at 0.300) indicate that some energy-intensive industries still contribute to emissions, particularly those relying on VMM. Regulations targeting high-emission industrial sectors are essential. URB's negative impact suggests DFI-enabled smart city initiatives can enhance sustainability, though their benefits need optimization to maximize environmental benefits. The dual impact of TOP implies in the short run, TOP reduces emissions (-0.432 to -0.702) by facilitating access to green technologies. The positive TOP(1) results (0.672 to 0.603), indicate that industrial expansion driven by trade increases emissions. FDI positive and non-significant results in VMM (0.372) and MMT (0.607) indicate that, in the short run, FDI favours polluting sectors before facilitating technology transfer. This study recommends FDI screening mechanisms to ensure investments align with sustainability goals from the outset. EC's positive impact (0.432 to 0.784) reinforces the need for energy-efficient DFI infrastructure. REN positive and non-significant results in some models (0.587 to 0.909**) reveal that transition costs initially increase emissions. REN(1) positive and significant results (0.171 to 0.770) indicate that inefficiencies in Nigeria's energy grid hinder REN's full benefits. The initial carbon costs of REN integration must be addressed through improved grid infrastructure and financial incentives.

Conclusion and policy implications

This study examines the interplay between DFI, and ENV within the EKC framework, using direct DFI indicators such as NMM, VMM, ADA, and MMT for a more precise analysis. Employing the DARDL model within an extended STIRPAT framework, the study evaluates both short- and long-term effects of DFI on ENV incorporating key structural factors IND, URB, EC, REN, FDI, and TOP to capture the broader economic and structural dynamics influencing ENV outcomes.

The results confirm an N-shaped EKC, where initial IEG degrades ENV ($IEG > 0$), at higher income levels, and adoption of greener technologies ENV improves ($IEG^2 < 0$), but rebound at very high-income levels due to intensified IND and financial globalization ($IEG^3 > 0$). IND reduces emissions in three models (-0.518 to -0.682) but increases emissions in the VMM model (0.112), indicating that energy-intensive digital finance services contribute to CO_2 emissions. URB significantly reduces emissions in most models (-0.614 to -0.718), except in VMM (0.680), where urban sprawl and increased energy use from digital infrastructure drive emissions. (TOP) initially increases emissions (0.230), in the long run, it reduces emissions (-0.536 to -0.741) through technology transfer. (FDI) significantly reduces emissions (-0.210 to -0.619), supporting the Pollution Halo Hypothesis. EC increases emissions in all models (0.332 to 0.702), emphasizing the need for cleaner energy sources. REN's initial adoption increases emissions (0.820,) in the long-term it reduces them (-0.901 to -0.892). ECM confirms a rapid convergence to long-run equilibrium, with CointEq(-1) values between -0.833 and -0.922, indicating that environmental shocks stabilize within 4-5 months. However, challenges such as limited digital infrastructure, low digital literacy, and transaction inefficiencies hinder its full potential. To align DFI with climate policies the government must promote green digital finance through incentivizing carbon-neutral banking, digital payments for green investments, and mobile finance for REN projects. Ensure FDI inflows support low-carbon industries while enforcing stringent ENV standards for trade and industrial activities. Leverage DFI to mobilize investments in clean energy infrastructure and ensure widespread awareness and adoption of sustainable digital finance solutions.

Recommendations

Given the N-shaped EKC, Nigeria should promote sustainable finance mechanisms, such as green bonds, carbon taxes, and investment in eco-friendly industries to prevent emissions resurgence at higher income levels. Policies should align IEG with strict ENV regulations to sustain long-term emission reductions. VMM's positive impact on emissions indicates that energy-intensive DFI operations contribute to ENV degradation. Policymakers should incentivize energy-efficient data centers, green fintech solutions, and e-waste recycling to reduce emissions from the digital finance sector. The short-run increase in emissions from REN adoption shows that grid inefficiencies and high transition costs hinder immediate benefits. The government should invest in smart grids, and decentralized REN systems, and provide subsidies for green energy investments to enhance REN's long-term effectiveness. While TOP initially increases emissions, long-run reductions indicate that green technology transfer is crucial. Trade policies should enforce environmental standards for imports and exports, ensuring industries adopt cleaner production methods. Since FDI reduces emissions in the long run, green FDI policies should be implemented to attract environmentally friendly investments.

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