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FINANCIAL INCLUSION, INSTITUTIONAL QUALITY, AND ENVIRONMENTAL MANAGEMENT IN NIGERIA

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Abstract

This study assesses the interactive nexus between digital financial inclusion (DFI), institutional quality (INQ), renewable energy (REN), inclusive economic growth (PGDP), and environmental sustainability (ENS) in Nigeria, using the Dynamic Autoregressive Distributed Lag (DARDL) model within the EKC-STIRPAT framework. The results confirm the N-shaped EKC hypothesis, where PGDP initially degrades ENS (0.389 to 0.720) and improves it at transitional income levels ($PGDP^2$: -0.810 to -0.812), but further economic expansion leads to renewed ENS degradation ($PGDP^3$: 0.673 to 0.82). The results reveal that DFI alone is insufficient to enhance ENS; however, DFI-INQ interaction significantly improves ENS (-0.614 to -0.871 in the long run; -0.560 to -0.712 in the short run), underscoring the importance of governance, regulatory enforcement, and green financial policies. Industrialization (IND) and urbanization (URB) exhibit mixed effects, while energy consumption (EC) degrades the ENS (0.324 to 0.731). REN enhances ENS in the long run (0.509–0.915), but imposes short-run trade-offs (-0.576 to -0.897). The ECM confirms rapid adjustments (-0.871 to -0.950), emphasizing Nigeria's financial system's responsiveness to ENS shocks. These results offer policy insights into leveraging DFI and INQ reforms to foster a sustainable financial ecosystem that balances PGDP with ENS.

Keywords: Digital Financial Inclusion, Institutional Quality, Environmental Sustainability.

1. INTRODUCTION

The increasing recognition of climate-related risks associated with global economic and financial activities has significantly intensified the urgency of balancing environmental sustainability (ENS) with inclusive economic growth (PGDP). Achieving this balance is critical for Nigeria, one of Africa's most climate-vulnerable nations, where economic expansion continues to strain environmental resources. In this context, financial inclusion

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(FI) has emerged as a pivotal driver of PGDP, facilitating businesses and households' access to financial services that can either accelerate ENS degradation or enhance its sustainability through investments in green finance and renewable energy (REN) (Samuel et al 2023; Udo et al 2023). FI, operating through digital inclusion channels (DFI) and classical inclusion channels (CFI), enables transition toward sustainable business models. DFI, leveraging on financial technology channels, like mobile and digital payment platforms, reduces the reliance on carbon-intensive financial systems, fosters resource conservation and sustainable consumption patterns, and alleviate involuntary financial exclusion caused by poverty, income inequality, and systemic market failures (Samuel et al., 2023; Udoh et al., 2018). However, DFI interactive effect of DFI on ENS also raises ENS concerns as it intensifies fossil fuel energy consumption (EC) through data infrastructure and mobile transactions.

This interaction introduces an unresolved tension between DFI, PGDP, and ENS. Qin et al. (2021) reveal that the DFI-ENS nexus follows a U-shaped pattern, where financial expansion depletes ENS; at the initial phase, as the economy evolves, ENS improves due to an increase in income level, leading to the adoption of REN, thus supporting the Environmental Kuznets Curve (EKC) (Renzhi & Baek, 2020; Inim et al 2024).

Conversely, CFI has been linked to ENS degradation owing to its potential to drive carbon-intensive consumption patterns. Zaidi et al. (2021), Udoh et al. (2024), and Inim et al. (2024) revealed that reliance on CFI for urbanization (URB), industrialization (IND), and PGDP exacerbates climate change. Although FI-driven growth fosters PGDP, its environmental trade-offs, such as IND and URB accelerate fossil fuel EC, contributing to ENS degradation. However, the effect of FI through DFI on ENS remains highly non-linear and context-dependent, raising critical questions about its role in Nigeria's sustainable development pathway. However, recent evidence reveals that this nexus may follow a more complex N-shaped pattern, where ENS first improves, then worsens, and stabilizes at higher levels of financial and economic development (Sun et al., 2022).

This study builds upon these insights by investigating whether the FI-ENS nexus in Nigeria, particularly within the context of DFI expansion, follows an N-shaped pattern. While DFI facilitates investments in REN and promotes green financial practices, it may also exacerbate ENS degradation directly or indirectly through data centers, ATMs, mobile banking network expansions, and fintech hubs (Zaidi et al., 2021; Udoh et al., 2024). Given Nigeria's rapid DFI where financial access surged from 24% in 2015 to 64% in 2022, this study empirically investigates DFI efficiency in balancing PGDP with ENS in the face of its dual effect.

Despite Nigeria's commitment to global climate initiatives, such as the Kyoto Protocol and the U.N. Sustainable Development Goals (SDGs), its ENS improved modestly by 3% between 2015 and 2022. Within the same period, Nigeria lost approximately 3.7% of its forests annually and contributed to a rise in global temperature rise (Hussain et al., 2023). The widening energy supply demand gap, with approximately 60%-70% of its population

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lacking access to electricity and relying on fossil fuel EC to drive IND, URB, and foreign direct investment (FDI) inflows, further exacerbates ENS concerns (Samuel et al., 2021).

Given this context, integrating REN sources and strengthening institutional quality (INQ) is pivotal for reshaping Nigeria’s EC patterns. REN sources, such as solar and wind energy, offer viable alternatives to fossil fuels and foster ENS. Udo et al. (2024) revealed that increased REN utilization is directly linked to improved ENS, making it a key driver of sustainable industrial activities. INQ encompasses governance effectiveness, regulatory frameworks, and anti-corruption measures, plays a crucial role in enforcing ENS stringent regulations, facilitating REN projects, and ensuring sustainable resource management. Emmanuel et al. (2023) further argued that nations with robust INQ enforce stringent ENS policies and incentivize sustainable business practices that lower emissions levels.

However, Nigeria’s governance framework, characterized by regulatory inefficiencies and corruption, questions the ability of financial digitalization to translate into meaningful ENS gains. While these insights highlight the significance of DFI, REN, and INQ, prior studies remain fragmented regarding their interplay in achieving ENS. These studies assessing DFI’s environmental implications rely on indirect measures, such as mobile network coverage and smartphone penetration, ignoring its practical and operational dimensions.

In addition, these studies characteristically examined the FI-ENS nexus in isolation (Ansari et al., 2023; Ali et al., 2022), neglecting the contributory roles of DFI and INQ in these linkages. Similarly, the role of REN as a key driver of ENS remains understudied within the FI discourse. Therefore, this study explores whether DFI its interaction with INQ and REN can mitigate the environmental trade-offs of PGDP and promote ENS.

Research Objectives and Contributions

While prior studies have examined the FI-ENS nexus, several gaps persist:

1. Fragmented evidence on DFI-ENS interactions: Prior studies primarily focused on CFI or adopted indirect DFI proxies (mobile penetration) rather than direct indicators of DFI to capture its adoption, usage, depth, and scope.
2. Neglect of the INQ and REN interactive factors: Extant studies assessing the FI-ENS nexus fail to account for the interactive effect of INQ on this nexus and how REN adoption interacts with DFI to enhance ENS.
3. Limited exploration of nonlinear EKC Dynamics: While extant studies assume a U-shaped FI-ENS relationship, emerging literature reveals an N-shaped pattern that remains underexplored in emerging economies, particularly Nigeria. Due to heavy reliance on fossil fuels and the informal financial sector, the adoption of DFI may trigger multiple inflection points in the FI-ENS nexus, lack of green finance incentives, lax regulatory enforcement, and misalignment between FI and REN policies.

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This study addresses these gaps by:

1. Empirically testing the N-shaped EKC applicability in the DFI, REN, and INQ interaction in Nigeria using the Dynamic Autoregressive Distributed Lag (DARDL) model within the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT)-EKC framework. The STIRPAT model provides a robust analytical approach to examine how population, affluence, technology, and DFI influence ENS outcomes.
2. Direct DFI indicators include the percentage of mobile Internet users with mobile money accounts (adoption), mobile money transactions (usage), and the value of mobile-based financial transactions (depth and scope) (Table 1). This study provides a more accurate assessment of FI's environmental implications of FIs.
3. Assessing the interactive role of INQ in shaping DFI's impact of DFI on ENS and capturing how governance quality influences financial-environmental linkages.
4. Structural break analysis was used to examine potential shifts in the FI-ENS relationship over time.

By focusing on Nigerian Africa's third-largest economy and one of its most climate-vulnerable nations, this study provides valuable insights into how DFI, INQ mechanisms, and REN can drive PGDP. The study results contribute to both policy and academic discourse, offering a framework that can be replicated across other emerging economies that face similar challenges. To enhance the validity of our results, we performed structural break analysis and stability diagnostics.

Table 1: Digital Financial Inclusion Indicators

Indicators	Justification
% Of mobile internet users with mobile money accounts (MMM)	Provides a direct measure of DFI adoption.
Mobile money transactions per 1,000 adults (MMT)	Reflects usage intensity and engagement with DFI.
Value of mobile-based transactions (VMB)	Offers insights into the depth and scope of DFI's economic influence.

Source; Authors (2024)

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

We examine the theoretical and empirical interactive effects of DFI, INQ and REN on ENS. We integrate multiple perspectives, including green finance theory, financial literacy theory, and environmental Kuznets curve (EKC) dynamics, to provide a comprehensive framework for understanding these interactions.

Green Finance Theory: The green finance theory and theoretical underpinnings of this study assess the interlink between DFI and ENS. Green finance aligns financial decision-making with ENS by prioritizing capital allocation to green projects such as REN, which

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ensures that financial flows support climate resilience and emissions reduction. The Paris Climate Agreement (PCA) further strengthens this framework by mandating signatory nations to develop green financing mechanisms. This theory is also critical for achieving SDGs, particularly those related to climate action, responsible consumption, and clean energy. By channeling financial resources into ENS beneficial activities, green finance promotes sustainable economic growth while mitigating ecological risks.

Financial Literacy Theory: Financial literacy theory underscores an individual's capacity to make informed financial decisions. Higher financial literacy fosters FI and PGDP, which in turn improves ENS (Ozturk & Ullah, 2021). In the digital era, financial literacy enables responsible financial behavior through DFI platforms, supporting green investments and energy-efficient consumption. A robust financial system supported by robust institutions and regulatory frameworks enhances DFI, enabling individuals and businesses to access credit for green projects. This interaction reveals the importance of financial literacy in leveraging DFI for ENS.

EKC and Non-linear FI-ENS Link

Studies exploring the EKC hypothesis propose a non-linear link between FI and ENS, where PGDP initially degrades ENS but improves ENS after reaching a certain threshold of development due to an increase in income level. Several studies support this notion, reporting inverted U-shaped and N-shaped links between FI and ENS (Renzhi & Baek, 2020; Grossman & Krueger, 1991). Qin et al. (2021) reported a U-shaped link between FI-ENS. Similarly, Hung et al. (2018) observed a non-linear link between FI and greenhouse gas (GHG) emissions in 25 OECD countries from 1971 to 2007. Expanding on these results, Grossman and Krueger (1991) proposed that the nexus between FI and ENS could follow an N-shaped pattern, with ENS initially improving, then worsening, and stabilizing at higher levels of FI. Sun et al. (2022), supporting this N-shaped nexus, reveal that this nexus is underexplored in emerging economies. These studies collectively posit that in the short to medium term, FI shows an inverted U-shaped link with ENS, while in the long term, an N-shaped relationship emerges as economies transition toward greener investments (Sun et al., 2022). This study explores whether such nonlinear dynamics exist in Nigeria, considering its unique financial and environmental contexts. Therefore, this study posits that the DFI-ENS link in the short-to medium-term may follow an inverted U-shape, while in the long-term it may follow an N-shaped nexus.

H_1: There is an N-shaped DFI- ENS nexus in Nigeria.

FI and ENS Link: The link between FI and ENS is multifaceted and complex across economies and financial structures. DFI enables households and businesses to access green credit facilities for the development and adoption of REN (Wan et al., 2021). Udo et al. (2024) reveals that FI through DFI channels supports eco-friendly practices through access to green financial products. Further empirical evidence reveals that DFI enhances ENS across various contexts by reducing cash-based transactions, facilitating remote work, and promoting mobile banking, thereby lowering carbon footprint (Li et al., 2021).

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Mobile money platforms and fintech innovations enable investment in green technologies and foster cleaner production and consumption patterns. In Nigeria, Udo et al. (2023) and Samuel et al. (2023) revealed that DFI channels such as mobile and online banking promote cashless transactions, thereby reducing the need for physical banking infrastructure. In emerging economies with high DFI adoption, ENS is improved due to increased financial access for sustainable projects (Al-Smadi, 2021). Blockchain technology further enhances transparency in green finance by tracking investment in eco-friendly initiatives. Nevertheless, excessive digital financial expansion can also lead to increased electronic waste and higher EC from data centers and digital infrastructure.

Similarly, Jiang and Ma (2019) and Wan et al. (2021) reveal that CFI, through increased access to physical banking infrastructure, contributes to ENS degradation due to higher fossil EC. Amin et al. (2022) attributed the negative environmental effects of FI in South Asia to a lack of coherent regional policies and coordination, arguing that aligning FI initiatives with ENS policies could mitigate these impacts. Quantitative analyses further upheld the view that FI may threaten ENS under certain conditions, such as the overexploitation of natural resources, lax environmental awareness, and regulations (Le et al. 2020; Inim et al 2023). Ahmad et al. (2022), using advanced econometric models, reported a positive link between FI and ENS in Nigeria, the BRICS economies, and the ASEAN region. Thus, effective governance is needed to ensure DFI's environmental benefits outweigh its ecological costs. Therefore, this study posits the following hypotheses:

H_2: DFI positively affects ENS.

REN-ENS Nexus

The investment and development of REN sources, such as solar, wind, and hydro energy, is extensively acknowledged as a decisive pathway for improving ENS and creating green jobs that reduce exposure to volatile fossil fuel markets (Fatima et al., 2022). However, ENS of REN is not entirely devoid of trade-offs. The short-term ENS costs are associated with REN adoption and the production of solar panels, wind turbines, and battery storage systems to improve ENS. In addition, the extraction of rare earth minerals, such as lithium, cobalt, and nickel, which are critical for REN development, degrades ENS through deforestation, soil degradation, and water pollution, particularly in resource-rich regions and countries, but is environmentally vulnerable (Zeng et al., 2023). Despite these concerns, technological advancements that improve the recycling of solar panels and wind turbine components mitigate the adverse environmental impacts of REN (Zhao et al., 2023). Furthermore, policy interventions, including stringent environmental regulations on mineral extraction and the promotion of sustainable supply chain practices, are crucial to ensure that the long-term benefits of REN offset its short-term ecological footprint. Hence, while REN remains a fundamental pillar of environmental sustainability, a holistic assessment that considers its life cycle impacts and sustainability trade-offs is essential for informed policymaking and responsible energy transitions. Based on the above literature, this study proposes the following:

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H$_3$: REN negatively affects ENS

INQ and ENS

INQ is a crucial determinant of ENS outcomes and facilitates the enforcement of stringent ENS policies and regulatory oversight, curbing sustainable ENS activities, such as deforestation, industrial pollution, and unregulated resource extraction (Jahanger et al., 2022). Studies on the INQ-ENS nexus show that economies with higher INQ, such as BRICS and OECD nations, exhibit stronger commitment to green financing, sustainable infrastructure development, and climate resilience through the incentivization of firms and individuals to adopt sustainable practices and invest in cleaner technologies (Rodrik, 2023; Fakher, 2021). Robust INQ facilitates access to ENS funds, promotes green bonds, and implements stringent carbon-pricing mechanisms that discourage unsustainable activities. In contrast, economies such as Nigeria with lax INQ frameworks struggle with policy implementation gaps, regulatory capture, and enforcement inefficiencies, leading to ENS degradation and resource mismanagement (Emmauel et al, 2023 Acemoglu & Robinson, 2022). However, the extent to which INQ influences ENS is contingent on sociopolitical stability, the rule of law, and regulatory effectiveness. While strong INQ drives positive ENS outcomes, political instability may lead to lax enforcement of ENS regulations despite formal institutional structures. Thus, a holistic approach that integrates INQ reforms, anti-corruption measures, and participatory governance is necessary to maximize the ENS benefits of high INQ. Therefore, this study proposes the following hypothesis:

H$_4$: INQ positively affects ENS.

DFI-INQ Interactive effect on ENS

DFI efficiency is significantly influenced by INQ, which provides capital for REN and green investments through mobile banking, fintech solutions, and digital lending platforms. However, without a robust INQ, DFI funds may be misused, leading to resource misallocation, fraudulent climate projects, and increased financial instability (North, 2021). Thus, INQ can strengthen DFI impact of DFI on ENS through improved climate finance governance. In this framework, blockchain technology has emerged as a decisive tool for tracking climate finance, mitigating greenwashing risks, and ensuring that funds designated for sustainable projects are not diverted for non-ENS purposes (Zhang et al., 2022).

The DFI-INQ interaction fosters green entrepreneurship through digital payment systems, crowdfunding platforms, and peer-to-peer lending. Institutionalized financial ecosystems ensure that green startups receive adequate funding while adhering to sustainability standards (Nathaniel et al., 2023). This interaction enables governments to implement carbon taxation, green subsidies, and digital incentives that reward environmentally responsible financial behavior. However, the effectiveness of this interaction depends on the extent to which INQ is adaptive to technological advancements. As such, regulatory rigidity slows down DFI adoption, whereas lax regulatory enforcement allows the

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proliferation of unsustainable financial products. Therefore, a balanced approach in which DFI is complemented by robust and adaptable INQ is essential to maximize its ENS benefits. Based on the literature, this study proposes the following hypothesis:

H_5: The interaction between DFI and INQ significantly impact on ENS.

Research Gap and contribution

Despite the growing literature on FI and ENS, critical research gaps persist, particularly in the context of DFI and INQ interactions in emerging economies such as Nigeria. As such:

1. Limited focus on DFI-ENS nexus: Prior studies exploring the FI-ENS nexus have focused on CFI, ignoring the transformative role of DFI. Studies focusing on DFI often rely on indirect proxies and ignore the operational aspects of DFI. However, empirical evidence of the non-linear dynamics of the DFI-ENS nexus in emerging economies remains scarce. This study contributes by analyzing whether DFI-ENS nexus in Nigeria exhibits an inverted U-shape or an N-shaped nexus in the short-to medium- and long-term. Thus, this study contributes to the broader debate on EKC in digital financial systems. By employing a direct DFI indicator, we capture both breadth (adoption rate) and depth (usage intensity). This study provides precise insights into the tradeoffs and synergies between financial expansion and environmental conservation.
2. INQ role in enhancing DFI's effect on ENS: Prior studies assessing DFI-ENS nexus ignored the contributive role of INQ. On the other hand, (Rodrik, 2023; Fakher, 2021), acknowledging the role of INQ in ENS focuses on CFI. This study examined how INQ modulates the effects of DFI on ENS. As lax, INQ can limit the effectiveness of DFI tools by enabling financial mismanagement, greenwashing, and inefficient capital allocation (Acemoglu & Robinson, 2022).
3. Lack of dynamic modeling approaches: Most studies use static models, which fail to capture the evolving and interactive nexus between DFI, INQ and ENS. This study employs the DARDL framework within the STIRPAT framework, which offers a comprehensive assessment of population dynamics, affluence, technological innovation, DFI expansion, and REN adoption in shaping Nigeria's ENS trajectory.

3. THEORETICAL FRAMEWORK

3.1 EKC and STIRPAT Models:

The EKC hypothesis, proposed by Grossman et al. (1995), proposes an inverted U-shaped link between inclusive growth (measured by per capita income (PGDP) and ENS. In the "pre-industrial phase," PGDP, IND and URB deplete ENS due to high energy consumption and lax regulatory frameworks. However, in the "post-industrial phase," technological advancements, robust INQ, and green finance mechanisms promoted a shift toward cleaner production and improvement in ENS. This transition aligns with SDGs

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7 (clean energy), 8 (inclusive growth), 13 (climate action), and 17 (global partnerships). Despite its heuristic value, the EKC faced substantial criticism for assuming a uniform trajectory for all countries, neglecting regional, institutional, and sectoral differences, overemphasizing PGDP as the primary driver of ENS, and ignoring factors such as financial inclusion, digitalization, and governance quality. To address these limitations, this study integrates DFI and INQ into EKC framework to examine whether the N-shaped EKC hypothesis holds in Nigeria.

The STIRPAT Model and Its Extension

The IPAT equation (Impact = Population (p) × Affluence (A) × Technology (T)), proposed by Ehrlich and Holdren (1971), while it provides a foundational framework for understanding human-induced ENS impacts, it has been heavily criticized for its deterministic and non-stochastic nature and for failing to account for variation across countries overtime. To address these limitations, Dietz et al. (1994) proposed the STIRPAT model, which incorporates stochastic elements to allows for different drivers of ENS: $I = aP^b \times A^c \times T^d \times \varepsilon^e \ldots\ldots\ldots\ldots\ldots\ldots (1)$

where a is a constant term; b,c, and d are elasticity coefficients; and ε is the error term.

While the STIRPAT model enhances the IPAT model by allowing empirical estimations of the dynamic nexus, it lacks the integration of financial and institutional variables that are critical determinants of sustainable development in emerging economies. To bridge this gap, we extended the STIRPAT framework by incorporating DFI, INQ, PGDP, and REN as the key drivers of ENS.

$$CO_2 = a \times P^b A^c \times T^d \times DFI^f \times REN^g \times URB^h \times IND^I \times EC^j \times INQ^k \times PGDP^l \times \varepsilon^{\varepsilon} \ldots (2)$$

Equation (2) allows for an interactive term (DFI × INQ), which captures how INQ moderates the influence of DFI on ENS.

Based on the extended STIRPAT model, the is specified as:

$$CO_2 = \beta_0 + \beta_1 DFI + \beta_2 REN + \beta_3 URB + \beta_4 IND + \beta_5 EC + \beta_6 INQ + \beta_7 PGDP + \beta_8 PGDP^2 + \beta_9 PGDP^3 + \beta_{10}(DFI \times INQ) + \varepsilon \ldots . (3)$$

A positive interactive term indicates that $DFI \times INQ$ enhances the effectiveness of DFI channels in promoting green investments and ENS.

EKC Model Specification

To test for nonlinearity, the quadratic and cubic effects of PGDP ($PGDP^2$ and $PGDP^3$) were captured in the model to assess whether the FI follows an N-shaped EKC pattern in Nigeria.

$$CO_2 = \beta_0 + \beta_1 PGDP + \beta_2 PGDP^2 + \beta_3 PGDP^3 + \mathrm{X} + \varepsilon \ldots\ldots\ldots\ldots . . (4)$$

β_1 = linear effect of PGDP on CO_2 emissions.

β_2 = quadratic effect (turning point).

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B_3= cubic effect, allowing for more complex relationships.

X = vector of other control variables that may influence CO2 emissions.

EKC Interpretation:

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

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

$\beta_3 > 0 =$ rebound in emissions after a certain threshold due to energy demand, INU, URB and industrial expansion.

The turning point (PGDP*) is calculated as PGDP* = $-\frac{\beta 1}{2\beta 2}$.

PGDP is adopted to reflect individual income levels, which aligns with the EKC mechanism, controlling for population effects and predicting the transition to sustainability, as higher personal income drives demand for green policies and technology. PGDP provides a more accurate measure of the economic-environmental relationship in the EKC framework, particularly for emerging economies, such as Nigeria.

By integrating DFI direct indicators, REN and INQ as key determinants of ENS into the EKC-STIRPAT frameworks, this study offers a novel and comprehensive dynamic understanding of how financial and governance systems shape ENS outcomes in Nigeria. The incorporation of nonlinear effects that validate the N-shaped EKC hypothesis and interactive terms allows for a nuanced analysis that captures the complexity of sustainable development in Nigeria and addresses gaps in existing studies that primarily test U-shaped relationships.

4. METHODOLOGY

This study investigates the interactive influence of DFI, INQ, REN on ENS and the validity of the EKC hypothesis in Nigeria from 2000 to 2023. The scope provides an optimal balance between DFI evolution, ENS policy changes, INQ reforms, and data availability, ensuring a robust empirical analysis of Nigeria’s DFI-ENS dynamics. Table 2 Variables and data sources.

DARDL Model Application

To assess the short- and long-term effects and interactive nexus between DFI, INQ, REN on ENS, the DARDL model was adopted to account for structural breaks due to policy shifts, regulatory changes, and technological advancements. This model is robust for handling mixed integration order (I(0) and I(1)) variables in time-series data, where some variables may be stationary, while others are non-stationary and can model dynamic interactions between variables. The baseline ARDL-ECM was modified as follows.

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

ECM specification: To capture the short-run dynamics,

$$\Delta CO_{2t} + \phi_0 + \sum_{j=1}^{k} \phi_1 \Delta CO2_2 + \sum_{j=1}^{k} \phi_1 \Delta DFI_{t-1} + \sum_{j=1}^{k} \phi_2 \Delta REN_{t-1} + \sum_{j=1}^{k} \phi_3 \Delta IND_{t-1} + \sum_{j=1}^{k} \phi_4 \Delta EC_{t-1} + \sum_{j=1}^{k} \phi_5 \Delta INQ_{t-1} + \sum_{j=1}^{k} \phi_6 \Delta(DFI * INQ)_{t-1} + \sum_{j=1}^{k} \phi_7 \Delta PGDP_{t-1} + \sum_{j=1}^{k8} \phi_8 \Delta PGDP^2{}_{t-1} + \sum_{j=1}^{k9} \phi_9 \Delta PGDP^3{}_{t-1} + \sum_{j=1}^{k10} \phi_{10} \Delta URB_{t-1} + \gamma_1 ECM_{t-1} + \varepsilon_{it} \ldots\ldots\ldots (6b)$$

where $\gamma_1 ECM_{t-1}$= speed of convergence to long-run equilibrium; γ_1 is expected to be negative and significant ($\gamma_1 < 0$), indicating a stable adjustment process; $\delta_8 > 0$; $\delta_9 < 0$; $\delta_{10} > 0$ (N-Shaped EKC Validation): $\delta_9 > 0$ or insignificant δ_{10} → Standard U-shaped EKC is valid.

Unit Root Test and Co-integration Tests

The unit root properties of the series were tested using the Augmented Dickey-Fuller (ADF) test and the Clemente-Montanes-Reyes test to account for structural breaks not captured by the ADF. The Bound test assesses long-run relationships, rejecting (H_0) of no co-integration if the calculated *F*-statistics is (>) the upper critical value at the 0.05% significance level. The series was also assessed for potential multicollinearity issues. The results are presented in Table 5 (panels A, B, and C, respectively). The model selection was based on the Akaike Information Criterion (AIC), and a lower AIC value was selected (see Table 6).

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Table 2: Variable Descriptions and Units

Variables		Indicators	Data Source
Carbon Footprint	CO_2emissions	Environmental Sustainability	World Bank Development Indicators (WDI) World Bank (2023)
Urbanization	URB	Urban Population	
Industrialization	IND	Manufacturing, value added (% of GDP)	
GDP per capita (constant $ 2015)	PGDP	Inclusive Growth	
Energy Consumption	EC	Fossil fuel energy consumption (% of total energy)	
Institutional Quality	INQ	Institutional quality index	
Renewable Energy	REN	Renewable energy consumption (% of total final energy consumption)	
% Of mobile internet users with mobile money accounts	MMA	Digital Financial Inclusion Channels	
No of mobile money transactions per 1,000 adults	MMT		
Value of mobile-based financial transactions	VMB		

Source: Author's Compilation (2024)

5. RESULTS AND DISCUSSIONS

Table 3: Descriptive Statistics

	Mean	Std. Dev.	Skewness	Kurtosis	Probability
CO2	0.58	0.12	0.06	2.10	0.41
EC	2.94	0.81	0.15	3.04	0.93
MMA	0.43	0.66	0.45	1.52	0.34
MMT	3.65	0.79	0.36	2.44	0.46
VMB	34.56	22.97	0.65	5.89	0.01
PGDP	7.81	0.17	0.95	2.25	0.13
IND	27.28	1.34	0.19	1.78	0.52
REN	4.42	0.26	0.10	2.09	0.68
INQ	2.83	1.08	0.66	2.61	0.46
URB	13.33	0.32	0.06	1.71	0.46

Source: Author's (2024)

The results in Table 3 provide critical insights into the DFI, INQ and ENS within the EKC-STIRPAT framework in Nigeria. Low CO2 emissions variability (mean: 0.58; Std. Dev.: 0.12) and near-normal distribution (skewness: 0.06, kurtosis: 2.10) reflect Nigeria's gradual transitions to sustainable energy consumption patterns, influenced by ENS policies such as the National Policy on Environment (1989, Revised 1999 and 2013) Renewable Energy Master Plan (REMP) (2005, Updated 2012) and Upstream Petroleum Decarbonisation Template (UPDT) (Effective January 2025).

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DFI channels (MMA, MMT, and VMB) exhibit moderate variations, indicating uneven penetration of digital financial services with high VMB variability (Std. Dev. = 22.97; Kurtosis = 5.89). This underscores regional imbalances in financial access, limiting DFI's full ENS benefits, unless INQ strengthens regulatory oversight.

INQ Moderate variability (Std. Dev. = 1.08; skewness = 0.66), and a normal-like distribution reflects governance differences, financial regulations, and institutional disparities across regions. Thus, limiting the full ENS benefits of DFI unless INQ is strengthened to enhance regulatory oversight and ensure equitable access. The interplay between DFI and INQ is crucial for determining whether DFI fosters green investment or exacerbates ENS degradation.

The minimal variability revealed by the PGDP (Std. Dev. = 0.17; skewness 0.95; and platykurtic distribution Kurtosis = 2.25) implies that Nigeria's economic growth is relatively stable but characterized by income disparities. Low IND (standard deviation) = 1.34) indicates steady manufacturing expansion without extreme fluctuations. As such, the EC with a mean value of (2.94) and. Dev. (0.81), revealing moderate variations in fossil fuel dependency. This implies that Nigeria's IND and PGDP are still fossil-fuel-driven, thus making the ENS transition challenging.

The REN mean value of (4.42) with a low Std. Dev. (0.26) and (skewness = 0.10) indicated low variability in the adoption of clean energy technologies. URB mean values of (13.33) and (skewness = 0.06) reflect a gradual but steady urban expansion in Nigeria. This implies that despite increasing urbanization, the non-significant REN integration can be attributed to institutional and infrastructural barriers that prevent large-scale REN. The positive skewness in PGDP (0.95) and moderate dispersion in IND (1.34) and EC (0.81) support the potential presence of a non-linear PGDP-ENS nexus.

Unit Root and Multicollinearity Tests

The ADF test results in (Table 4, Panel A) confirm stationarity at I(0) and I(1), justifying the use of the DARDL approach, which accommodates mixed integration orders but not I(2) variables. To enhance the robustness, the Clemente-Montanes-Reyes unit root test was conducted to confirm the stationarity results and detect structural breaks.

The results (Panel B) confirm the stationarity and structural breaks linked to major financial and energy sector reforms, 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 that there is no multicollinearity (all values are <10), ensuring robust estimations. This implies that the model variables are not closely linked to each other. These findings underscore DFI's potential to drive financial inclusion, reduce carbon reliance, and support clean energy transitions in Nigeria.

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Table 4: Unit Root Test Results

	ADF-Stat	Critical Values 5%	Order of Integration	T_{B1}	T_{B2}	*Test-statistics*	*K*	Multicollinearity
Panel A				***Panel B***				***Panel C***
Trend and Intercept								**VIF**
CO2	-5.563	-2.345	I(0)	2015	2017	-5.927	2	2.012
EC	-6.012	-3.812	I(0)	2008	2015	-6.215	3	4.362
MMA	-5.231	-2.301	I(1)	2000	2010	-6.687	2	5.240
MMT	-6.562	-3.510	I(0)	2015	2022	-5.890	2	5.221
VMB	-6.431	-2.421	I(0)	2005	2015	-4.052	2	5.151
INQ	-7.901	-3.120	I(1)	2000	2020	-7.051	1	6.014
PGDP	-9.011	-5.010	I(1)	2010	2020	-5.103	2	6.213
IND	-6.101	-4.134	I(1)	2009	2017	-7.982	2	6.205
REN	-6.214	-3.452	I(0)	2017	2022	-5.927	2	5.410
URB	-7.774	-3.052	I(1)	2007	2020	-4.687	2	4.111

Note: T_{B1} and T_{B2} signify the period of structural breaks (first and second); K lag length.

Source: Author's (2024)

5.1 Co-integrating Bound Test Results

The co-integrating bound test results (Table 5, Panel A) confirm a long-run co-integrating and interactive nexus between DFI, INQ, REN, PGDP, and ENS, with F-statistic values of <1(1) exceeding 5% critical bounds. This supports the premise that DFI enhances ENS by reducing fossil fuel reliance over time. On the premise of co-integration, the ECM was assessed to determine the speed of adjustment from short-run deviations caused by infrastructure gaps, digital energy demands, and financial adoption frictions converge to long-run equilibrium. The diagnostic test results (Table 5, Panel B) validate the robustness of the model, and the BG–Lagrange multiplier (LM) test for autocorrelation, which is (>0.5), confirms the absence of autocorrelation. The Breusch–Pagan Godfrey (BPG) test for heteroscedasticity confirms that the models are homoscedastic, and the Ramsey RESET affirms that the model is correctly specified without omission of relevant variables in the study. These findings reinforce the reliability of the proposed model and its implications for long-term financial and environmental policy planning.

Table 6: Autoregressive Distributed Lag (ARDL) Cointegration Test Results

Variables: DP: CO_2	Model	Test Statistics (5%)			Panel B: Diagnostic Tests (*p* values of the *F*-statistics)			
		F-stat	I (0)	I (1)	BG LM	BPG	ARCH Test (I)	Ramsey RESET test
MIU	2,2,2,1,0	10.029	2.730	4.163	0.610	0.429	0.511	1.419
MMT	3,3,3,3,3	9.551			0.532	0.441	0.617	2.301
VMB	4,4,4,3,4	13.526			0.700	0.674	0.408	1.116

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

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Table 7: ARDL Long and Short Run Model Estimate

Variables: **DP = CO_2 Emissions**	**Model 1** MIU	**Model 2** MMT	**Model 2** VMB
Long Run			
PGDP	0.389**	0.720**	0.634**
$PGDP^2$	-0.810**	-0.812**	-0.577**
$PGDP^2$	0.673**	0.619**	0.82**
IND	-0.695**	0.124**	-0.523**
URB	-0.730**	0.690**	-0.621**
INQ	-0.610*	-0.559**	-0.708**
EC	0.580**	0.324**	0.689**
REN	0.832**	0.509**	0.915**
(DFI*INQ)	-0.614**	-0.719**	-0.871**
Short Run			
CointEq (–1)	-0.871**	-0.848**	-0.950**
PGDP	0.551**	0.918**	0.909**
$PGDP^2$	-0.872**	-0.636**	-0.695**
$PGDP^3$	0.910**	0.734**	0.562**
IND	-0.311**	0.285*	-0.362**
URB	-0.240	----------	----------
INQ	-0.439**	-0.692**	-0.518**
TOP(1)	----------	0.669**	0.599**
EC	0.477*	0.423**	0.731**
EC(1)	0.918**	0.789**	0.373**
REN	-0.897**	-0.576**	-0.759**
REN(1)	-0.644**	-0.481**	-0.168**
(DFI*INQ)	-0.560**	-0.712**	-0.662**
Other Parameter Estimate			
R^2	0.987	0.812	0.973
Adjust. R^2	0.974	0.740	0.962
DW Star	2.11	2.35	1.65

Source(s): Author's (2024)

Discussion of the Long-Run Results in Table 7

The N-Shaped EKC Hypothesis (PGDP, $PGDP^2$, $PGDP^3$): The results confirm an N-shaped EKC in Nigeria, where PGDP initially degrades ENS, improves it at intermediate income levels, and leads to renewed degradation at high-income levels. The positive and significant PGDP coefficients (0.389, 0.720, and 0.634, respectively) indicate that increasing income initially increases emissions, reflecting industrial expansion and higher energy consumption. However, the negative and significant $PGDP^2$ coefficients (-0.810, -0.812, and-0.577) confirm an inverted U-shape, suggesting that structural transformation, green energy adoption, and environmental awareness reduce emissions as income reaches a critical threshold. At this turning point, proactive policy measures are required to prevent environmental rebound. The positive and significant $PGDP^3$ coefficients (0.673, 0.619, and 0.82) reinforce the N-shaped EKC, indicating that at very high-income levels, ENS may deteriorate again due to policy complacency, lax ENS

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enforcement, and resource-intensive economic expansion. The short-run results mirror this trend, highlighting the dynamic nature of the income-environment relationship. These findings support H1 and align with Grossman and Krueger (1991) and Sun et al. (2022). By integrating DFI-INQ within the EKC-STIRPAT framework, this study reveals that DFI's long-run impact of DFI on ENS depends on institutional effectiveness. This underscores the need for stringent financial regulations, sustainable finance policies, and technological innovations to prevent ENS at higher income levels.

DFI-INQ Nexus and its ROLE IN ENS: Results confirms that INQ (-0.610, -0.559, -0.708) negatively and significantly enhances ENS. The result underscores the critical role of governance, regulatory enforcement, and policy coherence in mitigating ENS degradation. The negative and significant DFI-INQ interaction term (-0.614, -0.719, -0.871) reveals that DFI alone is insufficient to improve ENS; however, when complemented by strong institutions, it facilitates green finance adoption and sustainable investments. The short-run estimates (-0.560, -0.712, and-0.662) reinforce this, showing that INQ reforms are key to directing financial resources toward environmentally friendly projects. These results support (**H_2 and H_4**) aligning with Wan et al. (2021) and Ullah et al. (2022), who argue that DFI fosters green investments, and corroborate Samuel et al. (2023), Udo et al. (2023, 2024), and Li et al. (2021), emphasizing DFI's role in cashless transactions and eco-friendly financial practices. However, they also validate the concerns of Jiang and Ma (2019) that unregulated financial expansion can degrade ENS, reinforcing the need for institutional oversight. These results align with those of Rodrik (2023) and Fakher (2021) regarding the positive role of INQ in promoting ENS.

IND, URB and EC- ENS Nexus: The impact of IND, URB and EC on ENS varies across models. The mixed IND effects (-0.695, 0.124, and-0.523) indicate that while clean technology adoption can enhance ENS, reliance on fossil fuels can degrade it. Short-run estimates confirm this dual effect, with Model 2 (0.285) showing a positive link, while the others indicate a negative impact. URB Similarly, URB exhibited both positive and negative effects (-0.730, 0.690, and-0.621), underscoring the need for sustainable urban planning to mitigate URB-induced environmental externalities. The positive and significant EC effects (0.580, 0.324, and 0.689) confirm that fossil fuel reliance remains a major driver of emissions in both the short and long run. These results emphasize the need for green industrial policies and clean energy transitions to ensure that IND and URB do not compromise ENS. The results align with the results by (Udo et al. 2024; Emmanuel et al. 2023; Wan et al. 2021; Samuel et al. 2021), reinforcing the need for eco-friendly industrial strategies and smart URB policies to balance PGDP with ENS.

REN-ENS Nexus: The results reveal that DFI enhances REN adoption. The long-run results (0.832, 0.509, 0.915) reveal that DFI facilitates access to digital financial services platforms to overcome the financial constraints that hinder REN investments. However, the short-run results (-0.897, -0.576, and-0.759) reveal a negative link between REN and ENS, suggesting that the initial ENS costs of renewable energy expansion may outweigh its benefits in the short term. This may be due to the ecological footprint associated with

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REN infrastructure development and the extraction of rare earth minerals for solar and battery technologies, which also degrades ENS if not managed sustainably. These findings support **(H_3)** and align with the findings of (Zhao et al. (2023; Inim et al. (024), highlighting the importance of policy interventions to mitigate the trade-offs in REN expansion.

Short-Run ECM Results

The CointEq (–1) values (-0.871, -0.848, and-0.950) indicate rapid convergence to the long-run equilibrium following a short-term shock. This result reveals the system's ability to correct short-term imbalances efficiently. This result implies that it will take the system for less than a year across all DFI channels, with VMB correcting fastest (≈8 months), MIU (≈9 months), and MMT taking slightly longer (≈10 months). The slow speed of convergence can be attributed to limited DFI infrastructure, low DFI literacy and awareness, behavioral preferences for cash transactions, and systemic challenges such as transaction failures and integration issues. In contrast, rapid VMB speed convergence in approximately eight months is driven by higher transaction volumes and the immediacy of mobile-based financial activities. Overall, these results suggest that DFI mechanisms in Nigeria are highly responsive and play a stabilizing role in financial systems and environmental policy implementation even in the face of short-term volatility. These findings align with (Samuel et al. 2023, Udo et al. 2023, Udoh et al. 2024, Ren et al. 2021).

6. CONCLUSION

This study examined the interactive interplay between DFI, INQ, REN PGDP, and ENS in Nigeria using the DARDL model within the STIRPAT-EKC framework. The results confirm the N-shaped EKC hypothesis, where PGDP initially degrades ENS, improves it at transitional income levels, but degrades it again at higher income levels (PGDP: 0.389–0.720; $PGDP^2$: -0.810 to -0.812; $PGDP^3$: 0.673–0.82). This result emphasizes the need for proactive policy interventions to prevent the third-phase rebound effect in ENS.

The results also reveal that DFI alone is insufficient to enhance ENS, but when complemented by strong INQ, it significantly improves ENS outcomes (DFI*INQ: -0.614 to -0.871 in the long run; -0.560 to -0.712 in the short run). This result confirms that effective governance, regulatory enforcement, and green financial policies amplify the DFI's environmental benefits. The necessity of INQ reforms to fully harness DFI for green investments is evident in the short- and long-run estimates.

IND and URB exhibit mixed effects on ENS. IND degrades ENS in MIU (-0.695) and VMB (-0.523) but improves ENS in MMT (0.124), highlighting the energy efficiency and structural composition of industries as key determinants. URB negatively impacts ENS in MIU (-0.730) and VMB (-0.621) but positively influences ENS in MMT (0.690), reflecting urbanization's dual role in pollution and sustainable development. EC consistently degrades ENS (0.324–0.689 in the long run; 0.423–0.731 in the short run), reinforcing the need for cleaner energy transitions. REN improves ENS in the long run (0.509–0.915) but

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temporarily degrades it in the short run (-0.576 to -0.897) owing to infrastructure expansion and material extraction costs.

The ECM results (-0.871, -0.848, and-0.950) indicate rapid adjustment speeds across different DFI channels, with VMB correcting faster (8 months), MMT (10 months), and MIU (9 months). This highlights the varying effectiveness of DFI mechanisms in addressing environmental shock. These findings contribute to the green finance and EKC-STIRPAT literature, emphasizing the critical role of DFI-INQ interactions in shaping sustainable development in emerging economies, such as Nigeria.

Recommendations and Policy Implications

1. Strengthening institutional quality for green finance: As DFI alone does not automatically enhance ENS, policymakers must prioritize institutional reforms to improve regulatory oversight, transparency, and financial governance. Strengthening anti-corruption measures and environmental regulations will ensure that green finance mechanisms (digital lending and carbon trading) are deployed effectively.
2. Balancing PGDP with ENS Protection: Confirmation of the N-shaped EKC hypothesis reveals that proactive policy interventions are needed at higher income levels to prevent environmental degradation. Implementing green taxation and subsidies for eco-friendly businesses would help maintain environmental gains beyond the intermediate income phase.
3. Enhancing the Role of Digital Financial Inclusion: Expanding DFI infrastructure (mobile banking networks and fintech-driven green investments) can accelerate clean energy adoption and eco-friendly financial behaviors. Policies should incentivize fintech firms to develop sustainable finance solutions such as blockchain-enabled green bonds and carbon credit trading platforms.
4. Industrial and Energy Sector Reforms: As industrialization has mixed effects on ENS, the government should encourage clean production technologies and circular economy models to reduce emissions. Given the positive impact of EC on CO_2 emissions, urgent steps should be taken in the transition from fossil fuels to renewables, including investments in solar, wind, and hydroelectric power.
5. Targeted Renewable Energy Policies: The short-run negative impact of REN on ENS reveals that policymakers must address the environmental costs associated with renewable infrastructure development. Implementing eco-friendly extraction and land-use policies could mitigate the initial environmental trade-offs of large-scale renewable energy expansion.

Overall, the study underscores that, while DFI enhances ENS, its effectiveness depends on INQ policy coherence. Future research should explore cross-country comparative analyses to assess the varying impacts of DFI, INQ, and green finance on ENS in other emerging economies.

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