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Nexus between digital financial services, renewable energy, and environmental sustainability in Sub-Saharan Africa

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Abstract

This study examines how digital financial services (DFS) influence environmental sustainability in Sub-Saharan Africa, with renewable energy considered as a complementary factor. Using a dynamic panel System-GMM model and data from 47 Sub-Saharan African countries spanning 1995 to 2022, the analysis explores both aggregated and disaggregated measures of DFS, including access and usage dimensions. The findings reveal that environmental sustainability is highly persistent, with past performance strongly shaping current outcomes. DFS access significantly improves environmental performance by enabling households and small firms to invest in renewable energy and sustainable practices, while DFS usage alone has little impact unless tied to green financial products. Renewable energy not only enhances sustainability directly but also amplifies the positive effects of DFS, confirming a strong complementarity between the two. Structural factors including foreign direct investment support sustainability, while population growth and resource-intensive economic expansion undermine it. The results suggest that DFS should be treated as a lever for climate action, with policies that expand access into underserved communities, embed renewable financing within digital products, and align investment flows with green development priorities.

Keywords: Digital Financial Services, Renewable Energy, Environmental Sustainability, System-GMM, Sub-Saharan Africa

JEL Classification: O33, Q42, Q56

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1. Introduction

Access to affordable, reliable, and sustainable energy remains a critical challenge in Sub-Saharan Africa (SSA). Despite abundant renewable energy resources, such as solar, hydro, wind, and geothermal, energy poverty persists at significant levels. As of 2022, approximately 570 million people in SSA lacked access to electricity, representing over 80% of the global population without electricity (Onyeanusi, 2025; Palm, 2025). In addition, nearly 900 million people across Africa continue to rely on traditional biomass sources, including firewood and charcoal, for cooking (Rauschenbach et al., 2024). This reliance contributes to environmental degradation through deforestation and greenhouse gas emissions, while undermining progress toward key Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy) and SDG 13 (climate action).

Energy poverty also reinforces socio-economic inequalities by constraining productivity, limiting educational attainment, and worsening health outcomes. For instance, a lack of electricity restricts students' study time and reduces access to digital learning tools. Women and children are disproportionately affected, often spending substantial time collecting firewood and engaging in traditional cooking practices, thereby reducing opportunities for education and income-generating activities (Drehobl et al., 2020; Rauschenbach et al., 2024). Consequently, addressing energy poverty is not only an environmental imperative but also a socio-economic priority.

In recent years, digital financial services (DFS) have emerged as a potentially transformative tool for addressing energy access challenges in SSA. DFS, including mobile money, digital payments, and mobile banking, have expanded rapidly across the region, improving financial inclusion and enabling innovative financing models. These services reduce transaction costs, enhance access to credit, and facilitate investment in energy infrastructure, particularly in off-grid and decentralised systems. For example, pay-as-you-go (PAYG) solar systems leverage mobile payment platforms, enabling low-income households to access clean energy technologies through flexible payment plans (Butu et al., 2021; Lee & Shepley, 2020; Montoya-Duque et al., 2022). The integration of DFS into the energy sector is particularly relevant in contexts where traditional financial systems are underdeveloped. By lowering barriers to financing, DFS can stimulate both demand for and supply of modern energy solutions. On the demand side, households can spread the cost of energy technologies over time, making them more affordable. On the supply side, firms can access digital payment systems to scale operations, improve revenue collection, and reduce default risks. This dual effect positions DFS as a critical enabler of energy transition in developing economies.

Despite these promising developments, empirical evidence on the relationship between digital financial services and energy poverty (Guang-Wen et al., 2023; Kirikkaleli & Adebayo, 2021; Wang et al., 2021) remains limited and inconclusive. Existing studies have primarily focused on the role of financial inclusion in economic development, with relatively less attention to its implications for energy access (Hunjra et al., 2023; Kirikkaleli & Adebayo, 2021; Yu et al., 2022).

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This gap is particularly pronounced in SSA, where both energy poverty and financial exclusion are most severe. Most studies focus on broad financial sector development rather than digital financial inclusion specifically, or examine SSA peripherally within global or multi-region analyses that fail to capture the region's distinct realities, including weak electricity grids, widespread informality, political instability, and stark rural-urban disparities (Hunjra et al., 2023; Kirikkaleli & Adebayo, 2021). Furthermore, few studies integrate financial inclusion, renewable energy, and environmental outcomes within a single analytical framework or deploy sufficiently robust econometric methods to address endogeneity and heterogeneity.

This study addresses these gaps directly. Using a dynamic panel System-GMM model and data from 47 SSA countries over the period 1995–2022, we examine how DFS, measured through both aggregated and disaggregated indicators of access and usage, influences environmental sustainability, with renewable energy considered as a complementary factor. The study makes four contributions. First, it foregrounds digital financial inclusion as a distinct driver of renewable energy adoption, distinct from general financial deepening. Second, it draws on Financial Capability Theory to explain how access to financial services empowers households to make sustainable energy choices. Third, the System-GMM approach yields reliable, bias-corrected estimates by addressing endogeneity, serial correlation, and unobserved country effects. Fourth, the SSA-specific focus generates targeted policy recommendations relevant to the region's institutional and infrastructural context. The findings directly inform SDG 7, SDG 13, SDG 1, and SDG 5, offering practical guidance for governments, development agencies, and financial institutions seeking integrated solutions to energy, environmental, and socio-economic challenges across the region.

The remainder of the paper is structured as follows: Section 2 reviews the theoretical and empirical literature. Section 3 outlines the methodology and data. Section 4 presents and discusses the results. Section 5 concludes with policy implications and directions for future research.

2. Literature Review

The relationship between financial inclusion and environmental sustainability is grounded in several complementary theoretical perspectives. A central argument is that inclusive finance enables sustainable energy transitions by improving households' capacity to adopt clean technologies. Evidence from African studies shows that financially included households are more likely to consume renewable energy, establishing a direct link between financial access and clean energy use (Kouton, 2021; Ofosu-Mensah Ababio et al., 2024). Access to savings, credit, insurance, and digital payments enhances the ability of households to invest in technologies such as solar panels and improved cookstoves (Kouton, 2021; Ofosu-Mensah Ababio et al., 2024). Furthermore, renewable energy adoption has been identified as a transmission channel through which financial inclusion contributes to reduced carbon emissions (Qin et al., 2021). This aligns with the concept of green financial inclusion, which emphasizes that expanding financial services

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to underserved populations can simultaneously advance social welfare and environmental sustainability (Ofosu-Mensah Ababio et al., 2024).

A growing body of literature highlights the role of digital financial services (DFS) in facilitating renewable energy adoption. DFS reduce transaction costs and address upfront affordability constraints through innovative financing mechanisms such as pay-as-you-go (PAYG) solar systems (Montoya-Duque et al., 2022). These models allow households to acquire solar home systems through incremental payments rather than large initial investments (Montoya-Duque et al., 2022; Oyedun et al., 2025). In East Africa, firms such as M-KOPA, BBOXX, and Fenix have leveraged mobile money platforms to scale solar adoption among low-income households (Baker, 2023). By enabling flexible payment systems and improving credit access, DFS have been theorized as critical drivers of decentralized energy expansion, particularly in off-grid contexts (Guo et al., 2025; Montoya-Duque et al., 2022). These mechanisms form part of a broader "theory of change" in which financial inclusion facilitates clean energy adoption, thereby promoting socio-economic development and sustainability (Butu et al., 2021).

Beyond household-level adoption, DFS also support renewable energy through enhanced financing of larger-scale green investments. The "green fintech" literature argues that digital platforms such as crowdfunding, peer-to-peer lending, and digital asset systems improve capital mobilization and allocation for sustainable projects (Sharma et al., 2025; Zaid et al., 2025). These tools reduce entry barriers for small-scale investors and entrepreneurs while increasing transparency in green finance. Empirical examples include the use of digital crowdfunding platforms to finance solar mini-grids and PAYG enterprises in Africa (Drehobl et al., 2020; Rauschenbach et al., 2024). Emerging technologies such as blockchain are also being explored for renewable energy financing, including trading renewable energy certificates and enabling community-based energy investments, although their application in Sub-Saharan Africa remains limited (Mhlanga, 2024). Overall, the literature suggests that DFS can accelerate renewable energy transitions by unlocking innovative financing models and expanding access to clean technologies (Ahmad et al., 2025).

The Green Inclusive Finance framework developed by the Center for Financial Inclusion further conceptualizes the role of financial services in environmental sustainability through four pathways: mitigation, resilience, adaptation, and transition (Novák et al., 2025). Mitigation involves reducing emissions through financing renewable energy, while resilience and adaptation focus on supporting vulnerable populations through instruments such as microinsurance and emergency credit (Mhlanga, 2024). Transition refers to facilitating broader shifts toward sustainable economic systems. DFS contribute across these pathways by enabling, for example, mobile-based solar financing and digital cash transfers for climate resilience (Drehobl et al., 2020; Rauschenbach et al., 2024). This framework underscores the growing recognition of digitally enabled financial

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inclusion as a key driver of climate and sustainability outcomes in Sub-Saharan Africa (Novák et al., 2025).

At the macro level, the interaction between financial inclusion and environmental outcomes has been examined within the Environmental Kuznets Curve (EKC) framework. The EKC posits that environmental degradation initially increases with economic growth before declining at higher income levels (Tenaw & Beyene, 2021). Extending this framework, some scholars propose an "inclusion–environment curve," suggesting that financial inclusion may initially increase energy consumption and emissions but eventually support cleaner growth through investment in green technologies (Mhlanga, 2024). Empirical evidence in Sub-Saharan Africa remains mixed. While some studies find that financial inclusion is associated with increased energy use and emissions due to expanded economic activity (Mukalayi & Inglesi-Lotz, 2023), others emphasize that these effects are non-linear and contingent on the availability of renewable energy alternatives (Alexander & Gleeson, 2022). This highlights the importance of aligning financial inclusion with green financing strategies to ensure sustainable outcomes (Zaid et al., 2025).

Empirical studies across Sub-Saharan Africa provide strong evidence that DFS contribute to improved energy access and reduced energy poverty. Using panel data from 36 African countries, Ajide et al. (2025) find that mobile money adoption significantly increases household access to electricity and modern energy sources, while also narrowing rural–urban disparities. These findings suggest that digital finance facilitates the diffusion of off-grid energy solutions, particularly in underserved areas (Ajide et al., 2025; de Almeida et al., 2020).

Micro-level evidence further supports this relationship. Studies in Kenya, Rwanda, and Zambia show that financial inclusion is positively associated with the adoption of grid electricity, solar systems, and clean cooking technologies (Kemabonta, 2025; Chishimba & Muchapondwa, 2025). Access to bank accounts and credit increases the likelihood of adopting modern energy solutions, while mobile money usage enhances energy access, particularly among female-headed households (Kemabonta, 2025; Chishimba & Muchapondwa, 2025). These findings highlight both the enabling role of DFS and the importance of contextual factors such as gender and country-specific conditions.

Real-world evidence reinforces these findings. East Africa's high mobile money penetration has coincided with rapid expansion of PAYG solar systems, with significantly higher adoption rates compared to regions with lower digital finance uptake (Chishimba & Muchapondwa, 2025). Kenya, in particular, demonstrates how mobile payment systems have enabled large-scale deployment of solar home systems through flexible financing models. Similar initiatives, such as Togo's CIZO program, illustrate how integrating digital payments with policy interventions can accelerate renewable energy adoption (Kohnert, 2025). These cases confirm that DFS reduce financial barriers and enhance access to decentralized energy solutions (Chishimba & Muchapondwa, 2025).

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However, the literature also identifies important limitations. Some studies find that fintech development may increase overall energy consumption without significantly improving the share of renewable energy, particularly in contexts where fossil fuels dominate the energy mix (Lang, 2025). This suggests that DFS-driven economic expansion can have unintended environmental consequences if not accompanied by investments in renewable energy infrastructure (Kemabonta, 2025). Despite these nuances, the overall empirical consensus is that DFS play a catalytic role in expanding clean energy access, especially when supported by complementary policies (Ajide et al., 2025; de Almeida et al., 2020).

Beyond household energy access, digital finance is increasingly being used to promote broader sustainability initiatives. Digital platforms such as green bonds and crowdfunding mechanisms are expanding access to financing for renewable energy projects (Lang, 2025; Ajide et al., 2025; de Almeida et al., 2020). Examples include Nigeria's digital green bonds and international crowdfunding platforms that support solar enterprises across Africa (Afolabi & Okundalaiye, 2025). These innovations demonstrate how fintech can democratize access to green investment opportunities and mobilize capital for sustainable development.

Additionally, DFS contribute to environmental sustainability through climate resilience and green innovation. Mobile-based financial products, such as agricultural microinsurance, support climate adaptation by enabling farmers to adopt sustainable practices while managing risk (Afolabi & Okundalaiye, 2025; Vosper, 2022). Technological innovations, including blockchain-based renewable energy certification systems, further enhance transparency and trust in energy markets (Marke et al., 2022; Njakatiana Andriarisoa, 2020).

Finally, mobile network operators are playing an increasingly important role by integrating renewable energy into their operations and partnering with clean energy providers. Initiatives such as solar-powered telecom infrastructure and mobile money–enabled energy services highlight the synergies between digital finance and sustainable energy systems (Prieto-Egido et al., 2020; Afolabi & Okundalaiye, 2025). These developments underscore the broader ecosystem through which DFS contribute to both energy access and environmental sustainability (Ajide et al., 2025; de Almeida et al., 2020).

3. Methodology

This study uses annual panel data from 47 Sub-Saharan African countries covering the period 1995 to 2022. Indicators of digital financial services are drawn from the World Bank Global Findex Database (2021, 2025), the IMF Financial Access Survey, and GSMA Mobile Money datasets, capturing access (account ownership, agent density), usage (number and value of transactions), and quality (service reliability, mobile coverage). Renewable energy is measured as both its share of total final energy consumption and its share of total electricity generation, sourced from the World Development Indicators and the International Energy Agency. Environmental sustainability is proxied by CO_2 emissions per capita, ecological footprint per capita, and the Environmental

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Performance Index from Yale's Center for Environmental Law and Policy. Control variables include GDP per capita, economic growth, population growth, trade openness, foreign direct investment, gross fixed capital formation, and the manufacturing share of GDP.

3.1 Estimation Strategy

Given the persistence of environmental outcomes and the potential endogeneity of financial inclusion and energy variables, the study employs the System Generalised Method of Moments (System GMM) estimator developed by Arellano and Bond 1995 and refined by Blundell and Bond 1998 (Akinbode et al., 2021). This estimator is well-suited to dynamic panel data with relatively large cross-sections and moderate time series, addressing simultaneity bias, unobserved heterogeneity, and endogeneity by using internal instruments. The baseline dynamic model is specified as:

$$ESI_{it} = \beta_0 + \beta_1 DFS_{it} + \beta_2 RE_{it} + \beta_3 X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (1)$$

Where ESI_{it} refers to the index of environmental sustainability, DFS_{it} refers to the index of Digital Financial Service, RE_{it} $refers\ to\ Renerwable\ Energy$, X_{it} refers to the vector of other macroeconomic variables used in the models. In subsequent equations, we estimate the effect of financial service access, financial service usage and quality of financial inclusion on environmental sustainability. In Equation 2 we introduce the interactive term or Renewable Energy

$$ESI_{it} = \beta_0 + \beta_1 ESI_{it-1} + \beta_2 DFI_{it} + \beta_3 RE_{it} + \beta_4 (DFI_{it} \times RE_{it}) + \beta_5 growth_{it} + \beta_6 pop\_growth_{it} + \beta_7 trade_{it} + \beta_8 tourism_{it} + \beta_9 FDI_{it} + \beta_{10} consumption_{it} + \beta_{11} manufacturing_{it} + u_i + v_i + \varepsilon_{it} \quad (2)$$

$where\ ESI_{it}$ refers Environmental Sustainability Index, DFS_{it} refers Digital Financial Services, RE_{it} refers to Renewable Energy, $GDPG_{it}$ refers to $GDP\ Growth$, $POPG_{it}$ refers to Population growth, $TRADE_{it}$ refers to Trade openness, $TOUR_{it}$ refers to Inbound tourism, FDI_{it} refers to Foreign Direct Investment inflows, $CONS_{it}$ refers to Final consumption expenditure, $MANUF_{it}$ refers to Manufacturing value-added, μ_i refers to Country-specific effects, ν_t refers to Time effects, ε_{it} refers to Error term.

3.2 Description and Measurements of Variables

Environmental Sustainability (ESI): The Environmental Sustainability Index (ESI) is a composite index that measures the overall progress towards environmental sustainability. It incorporates multiple indicators across several dimensions, such as air quality, water resources, biodiversity, and ecosystem vitality. The ESI provides a holistic view of how well countries are managing their environmental assets and dealing with environmental challenges. It is sourced from the database of the University of Yale Centre for Environmental Law and Policy.

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Digital Financial Service (DFS): This is an index created from two dimensions (financial service access, financial service usage). It is expected that digital financial services will positively influence environmental sustainability.

Digital Financial Service Access (FAccess): Measured as the number of bank branches per 100,000 adults, capturing the availability of financial institutions and services to households and firms (Chinoda & Kapingura, 2025). Sourced from the World Development Indicators.

Financial Service Usage (FUsage): Financial service usage refers to the actual utilisation of financial services by economic actors. It includes activities such as savings, borrowing, and making payments. Following studies (Soetan et al., 2021) financial service usage measured by the volume of loans and deposits.

Renewable Energy**:** The study employs renewable energy indicators to capture the role of clean energy in promoting environmental sustainability. Renewable energy is measured as the share of renewable sources—such as solar, hydro, wind, and biomass—in total energy consumption. Data are obtained from the World Development Indicators (WDI) and the International Energy Agency (IEA) databases.

Growth: This study utilises the annual growth rate of Gross Domestic Product to represent the economic growth rate. A nation's GDP functions as a critical gauge of its economic well-being. Gross Domestic Product (GDP) acts as a dependable measure of the economic vitality, income levels, and consumer demand within a nation. Elevated GDP figures are anticipated to communicate to investors that the economy is robust and possesses the capacity to sustain sufficient demand for their goods. Data was sourced from the World Development Indicators database.

Population growth: This is measured as the annual percentage increase in the population. Population growth can affect economic development, resource utilisation, and environmental sustainability (Yang et al., 2023). High population growth rates can strain resources and infrastructure. Data was sourced from the World Development Indicators database.

Trade: This is measured as the sum of imports and exports as a percentage of GDP. It indicates exposure of the environment through global value chains (S. Wang et al., 2021). Data was sourced from the World Development Indicators database.

Inbound Tourism: Inbound tourism refers to non-residents traveling to a country for leisure, business, or other purposes. It is measured by the number of tourist arrivals. Inbound tourism can significantly impact a country's economy by generating foreign exchange, creating jobs, and promoting cultural exchange. It can also put pressure on local infrastructure and natural resources (Khan et al., 2020). Data was sourced from the World Development Indicators database.

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FDI: Foreign Direct Investment is measured as the net of inward foreign investment and outward investments as a percentage of GDP. Data was sourced from the World Development Indicators database.

4. Results and Discussion

Table 1 presents a summary of variables used in the study. With a mean value of 44. 325 and a standard deviation of 23. 066, the Environmental Sustainability Index reveals significant regional variation around essentially moderate scores. Some regions still have major environmental issues even though others are going toward sustainability. Particularly vulnerable to climatic change and resource depletion is the sub-Saharan part of Africa. The mean of 12. 743 and standard deviation of 12. 209 for access to financial services show that the degree of financial access differs widely inside the region. Among the financial inclusion indicators, financial usage has the mean highest (60. 798) and standard deviation (46. 312), while the minimum value of 0. 02 shows that certain areas have quite low levels. High financial inclusion in a place implies a great degree of financial activity, but it also implies a big disparity between the most and least active areas. Additionally, the quality of financial services has a mean value of around 15. 842 with a minimum and a maximum value of around 104. 849.

Table 1. Table showing Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
ESIndex	1316	44.325	23.066	0	100
DFS	1316	4.877	1	-.942	7.282
gdp_growth	1273	4.302	6.976	-36.392	149.973
pop_growth	1315	2.484	1.212	-16.881	16.626
Trade	1100	68.16	34.445	2.699	235.82
Fdi	1269	4.32	9.288	-17.292	161.824
Inboundtourism	938	835131.24	1760563.4	2900	15121000
Gfcf	1054	20.908	9.155	-2.424	78.001
Consumption	1052	15.033	7.484	2.047	62.133
Manufacturing	1108	10.619	5.877	.233	35.215

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DFS Access	1316	12.743	12.209	.02	92.53
DFS Usage	1316	60.798	46.312	.02	358.72

Table 1 also shows that GDP growth in sub-Saharan Africa over the period has averaged about 4.302 percent with some countries experiencing negative growth over the period, while others have a maximum percentage growth of GDP of about 149.973.

Table 2: Results of Pairwise Correlation Test

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(1) ESIndex	1.000											
(2) DFS	0.074	1.000										
(3) gdp_growth	-0.139	-0.046	1.000									
(4) pop_growth	-0.157	-0.284	0.128	1.000								
(5) trade	-0.026	0.497	-0.001	-0.250	1.000							
(6) fdi	-0.145	0.117	0.249	0.073	0.351	1.000						
(7) inboundtourism	0.053	0.040	-0.047	-0.232	-0.025	-0.074	1.000					
(8) gfcf	-0.123	0.234	0.150	0.069	0.474	0.438	-0.051	1.000				
(9) consumption	0.047	0.293	-0.129	-0.246	0.444	0.063	0.090	0.196	1.000			
(10) manufacturing	0.066	-0.121	-0.098	-0.237	0.131	-0.176	0.183	-0.169	0.082	1.000		
(11) DFS Access	0.037	0.726	-0.086	-0.326	0.381	0.010	0.390	0.116	0.344	0.043	1.000	
(12) DFS Usage	0.023	0.531	-0.073	-0.254	0.236	0.000	0.039	0.051	0.292	0.033	0.692	1.000

Table 2 shows the pairwise correlation matrix of the independent variable employed for the analysis. The result of the pairwise correlation shows that most of our independent variables are moderately correlated and thus, do not raise the suspicion of multicollinearity. We therefore proceed with the estimations of the models.

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Table 3. Effect of Aggregated Financial Inclusion and Renewable Energy on Environmental Sustainability

Variable	(1) esindex	(2) esindex
L.esindex	0.861***	0.829***
	(0.0312)	(0.0425)
Inclusion	0.0915***	0.142**
	(0.0248)	(0.0591)
Renewable Energy	—	0.163**
		(0.0714)
Inclusion × Renewable Energy	—	0.172**
		(0.0765)
gdp_growth	0.00984***	0.00241
	(0.00365)	(0.00318)
pop_growth	0.0321	-0.108***
	(0.0583)	(0.0347)
Trade	-0.00205**	0.00011
	(0.00098)	(0.00101)
Fdi	0.0203***	0.0237***
	(0.00602)	(0.00718)
log_tourism	-0.0378**	-0.0691**
	(0.0172)	(0.0276)
Consumption	0.00321	-0.00872**
	(0.00211)	(0.00394)
Manufacturing	0.0467***	0.0215*
	(0.0135)	(0.0112)

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Constant	0.417	1.578***
	(0.392)	(0.584)
Observations	574	523
No. of Instruments	34	34
AR1 (P-Value)	0.412	0.337
AR2 (P-Value)	0.768	0.622
Hansen-J (P-Value)	0.203	0.289

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.0

The dynamic panel results reveal that the lagged environmental sustainability index remains positive and highly significant across the two specifications, indicating that past levels of sustainability strongly predict current performance. This confirms the persistence of environmental outcomes in Sub-Saharan Africa, where past investments in clean energy or conservation programs continue to shape future trajectories. Such persistence is consistent with the findings of Jamatutu et al. (2024) and Mulugetta et al. (2022) who emphasise the cumulative benefits of long-term environmental policy interventions.

Financial inclusion continues to emerge as a significant determinant of environmental sustainability. In the baseline model, a one-point increase in financial inclusion improves sustainability by about 0.0915 percent, while the effect rises to 0.142 percent when renewable energy is introduced. This pattern suggests that inclusive financial systems provide the foundation for environmental gains, but the impact is amplified when clean energy options are available. The results align with Ansari et al. (2025) and Ononogbo et al. (2024) who find that access to finance enables households and small businesses to adopt eco-friendly technologies such as drip irrigation, biogas plants, and solar home systems. In contrast, the findings contradict Khan et al. (2022), who argue that financial deepening in developing economies can worsen environmental outcomes by fueling unsustainable consumption. In this context, the evidence supports Ecological Modernization Theory, highlighting the ability of inclusive financial systems to drive green transitions when combined with renewable energy.

Renewable energy exerts a strong positive effect on environmental sustainability, consistent with Faizi et al. (2025) who argue that renewable deployment reduces dependence on biomass and fossil fuels. More importantly, the interaction term between financial inclusion and renewable energy is positive and significant, underscoring a complementarity effect. This finding indicates that

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inclusive financial systems amplify the benefits of renewable adoption by providing the capital needed to finance small-scale solar projects, mini-grids, or clean cookstove programs. Evidence from Kenya and Rwanda shows that mobile banking and microfinance schemes have enabled smallholders and households to adopt renewable energy technologies, reducing reliance on kerosene and firewood (Otundo Richard, 2024). This resonates with Stakeholder Theory (Freeman, 1984), which emphasises the value created when financial institutions, households, and energy providers act in concert toward sustainability goals.

The control variables provide additional insights. Economic growth has a positive effect in the baseline model but becomes insignificant once renewable energy is added, suggesting that growth alone does not guarantee sustainability unless accompanied by a structural shift toward clean energy. This pattern is consistent with the Environmental Kuznets Curve hypothesis and the evidence from (Sarkodie & Ozturk, 2020). Population growth is negative and significant in the second model, reflecting demographic pressures on land, energy, and natural resources, a finding that supports Maja and Ayano (2021). Trade openness has a weakly negative effect, consistent with the pollution haven hypothesis, while foreign direct investment is consistently positive, confirming the results of Dong et al. (2021) that multinational firms often transfer cleaner technologies and enforce stronger environmental standards. Tourism, on the other hand, is negative and significant across both models, highlighting the environmental costs of unregulated mass tourism, a result that mirrors the findings. Consumption turns negative once renewable energy is added, suggesting that current consumption patterns remain carbon-intensive, while manufacturing is positive and significant, indicating that industrial upgrading and cleaner production processes are beginning to improve sustainability outcomes, contrary to the expectations of Sarkodie and Ozturk (2020).

The diagnostic tests confirm the robustness of the estimates. The AR(2) statistics indicate no second-order autocorrelation, and the Hansen-J tests show that the instruments are valid. Overall, the results demonstrate that financial inclusion and renewable energy jointly enhance environmental sustainability in Sub-Saharan Africa. Financial access enables households and firms to adopt renewable solutions, while renewable energy strengthens the environmental returns to financial deepening. Structural drivers such as FDI and cleaner manufacturing reinforce these effects, whereas population pressure, unsustainable consumption, and unregulated tourism continue to undermine progress. These findings highlight the importance of aligning financial inclusion strategies with renewable energy policies to accelerate the achievement of Sustainable Development Goals 7 (affordable and clean energy) and 13 (climate action) in the region.

In table 4, we estimate the disaggregated effect of financial inclusion on environmental sustainability. We use three disaggregated measures of financial inclusion, including financial access, financial usage of financial service. The test of instrument overriding restrictions and serial

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autocorrelations indicates that the instruments used model are valid and that the model does not suffer the presence of first order serial correlation. To tackle the presence of endogeneity, the first lags of the variables are used as instruments.

Table 4. Disaggregated effect of Digital financial Service

	(1) fin_Access	(2) fin_Access	(3) fin_Usage	(4) fin_Usage
L.esindex	0.9736*** (0.0215)	0.7349*** (0.0119)	0.9085*** (0.0069)	0.9147*** (0.0175)
Inclusion	0.0346** (0.0472)	0.0148* (0.0168)	0.0016 (0.0264)	0.0031 (0.0354)
RE		0.4394*** (0.0188)		0.2568*** (0.0486)
Inclusion*RE		0.0176* (0.0482)		0.0007 (0.0133)
gdp_growth	-0.0198* (0.0254)	-0.0044 (0.0157)	-0.0109* (0.0150)	-0.0144* (0.0028)
pop_Growth	-0.4623*** (0.0309)	-0.1280*** (0.0256)	-0.1464*** (0.0035)	-0.0856*** (0.0147)
Trade	0.0001 (0.0455)	-0.0013 (0.0127)	-0.0017 (0.0081)	-0.0021 (0.0250)
Fdi	0.0535*** (0.0493)	0.0302** (0.0129)	0.0339** (0.0339)	0.0306** (0.0383)
Tourism	0.0640*** (0.0126)	-0.0680*** (0.0367)	0.0048 (0.0190)	-0.0699*** (0.0320)
Consumption	0.0040 (0.0320)	-0.0063* (0.0273)	0.0000 (0.0054)	-0.0021 (0.0419)
Manufacturing	-0.0594*** (0.0167)	0.0334** (0.0101)	-0.0117* (0.0030)	0.0121* (0.0300)

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Constant	1.3998*** (0.0342)	1.7650*** (0.0018)	0.9743*** (0.0261)	1.8714*** (0.0121)
Observations	574	523	574	523
No. of Instruments	33	33	34	34
AR1 (P-Value)	0.205	0.223	0.323	0.135
AR2 (P-Value)	0.160	0.422	0.301	0.596
Hansen-J(P-Value)	0.252	0.278	0.219	0.275

In Table 4, the first model focuses on financial access. The lagged dependent variable remains highly significant, with a coefficient of 0.9736, showing that past sustainability levels have a strong influence on current performance. This persistence underscores the importance of consistency in environmental policies, as highlighted by (Manu & Asongu, 2025) who emphasise the path-dependent nature of environmental outcomes. Financial access itself is positive (0.0346), indicating that a one-point increase in access leads to higher sustainability. Within the SSA context, this translates into households and SMEs using digital financial services (DFS) like mobile money and agent banking to secure credit and savings for renewable technologies or sustainable farming practices Ansari et al. (2025). Population growth exerts a negative effect (–0.4623), reinforcing the demographic pressures on resources noted by Dong et al. (2021). By contrast, FDI contributes positively (0.0535), suggesting that inflows of international capital improve sustainability through technology transfer Dong et al. (2021). Tourism is also positive in this specification (0.0640), pointing to eco-tourism's potential when regulated, while manufacturing shows a negative effect (–0.0594), reflecting the environmental costs of traditional industries. DFS, particularly through green credit and micro-loans, could help reorient manufacturing and tourism sectors towards sustainability.

The second model incorporates renewable energy, and the results are striking. Renewable energy itself is strongly positive (0.4394), highlighting its central role in reducing environmental pressures. The interaction between financial access and renewable energy (0.0176) is also significant, showing that access to finance amplifies the benefits of renewable adoption. Evidence from Kenya's PAYGo solar programs supports this, where mobile banking platforms allow households to spread payments for solar systems (Baker, 2023). Financial access remains positive though smaller (0.0148), suggesting that once renewable energy is accounted for, its role shifts from being a direct driver to an enabler. Population growth continues to undermine sustainability

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(–0.1280), while FDI remains beneficial (0.0302). Tourism turns negative (–0.0680), suggesting that in the presence of renewable energy, the harmful impacts of mass tourism become more visible, echoing (Li et al., 2024). Consumption also shows a negative effect (–0.0063), consistent with the carbon intensity of household demand in SSA. Manufacturing, however, shifts to positive (0.0334), showing that renewable adoption helps industries upgrade towards cleaner production, consistent with (Sarkodie & Ozturk, 2020). DFS complements this by financing energy-efficient technologies in industry and making renewables more affordable to households.

The third model examines financial usage. While the lagged dependent variable remains significant (0.9085), financial usage itself is not, underscoring that simply increasing transactions does not enhance sustainability unless linked to green products. However, GDP growth is negative (–0.0109), showing that SSA's growth patterns remain resource-intensive, echoing the early stages of the Environmental Kuznets Curve (Sarkodie & Ozturk, 2020). Population growth continues to weigh heavily on sustainability (–0.1464), while FDI supports improvements (0.0339). Manufacturing remains negative (–0.0117), reflecting traditional industry's environmental costs. The DFS implication here is clear: usage must be structured through targeted products, such as mobile-enabled green loans or digital savings accounts for solar adoption, in order to deliver sustainability gains Khan et al. (2022).

The fourth model combines financial usage with renewable energy. Renewable energy continues to be a significant driver (0.2568), confirming its importance. GDP growth (–0.0144) and population growth (–0.0856) remain negative, while FDI contributes positively (0.0306). Tourism is negative (–0.0699), reinforcing the risks of unregulated tourism expansion. Manufacturing turns positive (0.0121), once again showing that renewable energy enables industries to shift toward greener production. In this model, DFS can play a catalytic role by financing renewable adoption within industries and households alike, ensuring that financial usage channels environmental gains rather than neutral activity.

The four models consistently highlight the persistence of sustainability outcomes and the critical roles of financial access, renewable energy, and FDI. The coefficients reveal that a 0.0346 increase in access, a 0.4394 rise in renewable energy, and a 0.0535 increase in FDI are all associated with higher sustainability, while GDP and population growth show consistent negative impacts. Tourism and manufacturing vary depending on context, positive when linked to eco-tourism and renewable energy, but negative otherwise. The unifying message is that digital financial services strengthen these dynamics by expanding access, making renewable adoption affordable, and channelling capital into green sectors. By aligning DFS innovations with sustainability goals, SSA can transform finance into a lever for inclusive and environmentally sustainable development.

5. Conclusions and Recommendations

This study examined the nexus between digital financial services (DFS), renewable energy, and environmental sustainability across 47 Sub-Saharan African countries from 1995 to 2022. Using a

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dynamic panel System-GMM approach, the findings offer several important insights into how inclusive digital finance can serve as a lever for environmental progress in a region confronting simultaneous challenges of energy poverty, demographic pressure, and climate vulnerability.

A first and consistent finding is the strong persistence of environmental sustainability outcomes. The significance of the lagged dependent variable across all model specifications confirms that past environmental performance powerfully shapes current trajectories. This path dependency has an important implication: early and sustained investments in DFS-enabled clean energy initiatives generate compounding benefits over time. Conversely, delayed action risks locking countries into resource-intensive development pathways that become increasingly costly to reverse. Second, DFS access emerges as a more consistent and meaningful driver of sustainability than usage alone. At the aggregate level, a one-point increase in financial inclusion improves the Environmental Sustainability Index by approximately 0.09 percentage points in the baseline model, rising to 0.14 when renewable energy is introduced. Disaggregated results confirm that it is the reach of digital platforms rather than the sheer volume of transactions, that generates environmental gains. This distinction matters: expanding digital financial infrastructure into rural and peri-urban areas gives households the financial means to invest in renewable technologies, adopt climate-smart agriculture, and transition toward cleaner livelihoods.

Third, renewable energy plays a transformative and amplifying role. Its direct effect on sustainability is strong and consistent across all specifications, and the positive interaction between DFS and renewable energy confirms that these two factors are genuine complements. Together, they produce greater environmental gains than either would achieve independently. Evidence from PAYGo solar programs in East Africa illustrates this complementarity in practice, showing how mobile money platforms make renewable adoption affordable and accessible for low-income households who would otherwise remain dependent on kerosene and biomass. Fourth, the structural and macroeconomic environment shapes how effectively DFS and renewable energy translate into sustainability gains. Foreign direct investment consistently supports sustainability, likely through the diffusion of cleaner technologies and stronger environmental standards. By contrast, population growth and GDP growth both exert negative effects, reflecting the resource intensity of SSA's current development path and the mounting pressure of demographic expansion on land, water, and energy systems. Tourism and manufacturing show context-dependent effects: harmful when unregulated or fossil-fuel dependent, but positive when linked to eco-tourism and renewable energy integration respectively.

The findings generate several interconnected policy priorities. First, expanding DFS infrastructure into rural and underserved communities (through mobile money networks, agent banking, reduced KYC barriers, and platform interoperability) is foundational, given that access rather than usage volume drives sustainability gains. Second, renewable energy financing must be embedded directly within DFS products: scaling PAYGo solar schemes, digital green loans, and climate-

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focused savings accounts, supported by green credit guidelines from central banks and blended finance facilities from development institutions such as the African Development Bank, would institutionalize the DFS-renewable energy complementarity identified in this study. Third, DFS usage must be made purposeful through intentional product design, linking digital credit, insurance, and savings instruments explicitly to green activities such as clean cooking, solar irrigation, and low-carbon manufacturing, rather than allowing them to reinforce unsustainable consumption patterns. Fourth, DFS platforms should be leveraged to attract and direct green foreign investment by reducing transaction costs, enhancing transparency, and creating digital investment corridors that connect international climate capital with local renewable projects.

5.1 Future Research Directions

This study opens several avenues for future inquiry. First, while DFS access is shown to drive sustainability gains, the mechanisms through which different product types (green credit, mobile savings, PAYGo schemes) influence household and SME investment in clean energy deserve closer examination through both micro-level surveys and country-specific case studies. Second, the null finding on DFS usage warrants further investigation: future research should explore whether usage effects are contingent on the type of financial product, the gender of the user, or the local availability of renewable alternatives. Third, as blockchain-based green finance instruments and digital carbon markets begin to emerge in SSA, research should assess their scalability and potential to attract international climate finance.

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