

Transforming Finance for Sustainable Development in Sub-Saharan Africa: Financial Inclusion, Digitalisation, and Institutional Quality

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Abstract

Financial system expansion can support sustainable development in Sub-Saharan Africa (SSA), depending on financial inclusion, digitalisation, and institutional quality. This study investigates the nonlinear relationship between financial development and sustainability outcomes using panel data for selected SSA economies from 2011 to 2024. Sustainability is measured through carbon emissions, renewable energy consumption, and electricity access. The empirical analysis employs the Cross-Sectionally Augmented Autoregressive Distributed Lag model, Dynamic Common Correlated Effects Mean Group estimator, Method of Moments Quantile Regression, and dynamic panel threshold models to account for cross-sectional dependence, heterogeneity, distributional variations, and institutional thresholds.

The findings reveal that financial development may initially intensify environmental pressures, but its sustainability effects improve beyond identifiable financial maturity thresholds. Financial inclusion and digitalisation are associated with reduced carbon emissions, increased renewable energy consumption, and improved electricity access. Institutional quality further strengthens these relationships, highlighting governance capacity as a critical factor determining whether financial expansion reinforces carbon-intensive growth or facilitates sustainable transitions. The study demonstrates that financial development alone may not guarantee sustainability gains. Coordinating financial sector expansion with inclusive financial access, digital transformation, and stronger institutions is essential for advancing environmentally sustainable and inclusive development pathways across SSA.

Keywords: Financial development; Financial inclusion; Digitalisation; Institutional quality; Sustainability transitions; Sub-Saharan Africa.

1. Introduction

Pursuing sustainable development has become a defining global priority for governments worldwide, as reflected in the United Nations Sustainable Development Goals (SDGs), the Paris Climate Agreement, and successive international commitments to reconcile economic prosperity with environmental integrity (Bonnedahl et al. 2022; United Nations 2025). Yet despite decades of policy attention, the translation of these commitments into tangible outcomes remains uneven. A central challenge is whether economies can achieve not only growth but also structural transformation capable of simultaneously advancing development and environmental sustainability. This challenge is particularly acute in the relationship between financial systems and the environment, where conventional economic logic emphasises finance as a catalyst for growth, but emerging evidence suggests that financial expansion may generate both opportunities and risks for sustainability outcomes.

Traditional economic perspectives regard financial development as essential for growth through improved capital mobilisation, investment efficiency, and resource allocation. Deeper financial systems are expected to stimulate productive activities and enhance economic performance (Ofori-Sasu et al. 2024). However, whether expanding financial systems necessarily contributes to sustainable development remains unclear. Financial expansion may improve access to capital and facilitate technological upgrading, enabling cleaner production and energy efficiency (Fan et al. 2025; Wu and Ziqi 2025). Yet it may equally reinforce environmentally intensive production structures by financing fossil fuel dependence, unsustainable urbanisation, and resource-intensive industrial activities (Zeng et al. 2024; Ahmad et al. 2025). Consequently, financial development is a double-edged sword: it can accelerate growth but may lock economies into carbon-intensive pathways unless deliberately steered toward sustainable outcomes.

This ambiguity reflects a broader limitation within existing literature on the finance–environment nexus. Much empirical evidence assumes linear relationships, implicitly treating the sustainability effects of finance as constant across countries and development stages. Such assumptions overlook the possibility that financial systems evolve and that their environmental consequences may change as economies become more financially mature, technologically advanced, and institutionally developed. The sustainability effects of finance may therefore be fundamentally nonlinear, characterised by transition points beyond which financial expansion shifts from intensifying environmental pressure to supporting sustainable outcomes. Moreover, recent evidence increasingly suggests that financial systems should not be viewed solely through the lens of financial depth. Broader dimensions—including financial inclusion and digitalisation—may significantly alter how financial resources are accessed, distributed, and utilised. Financial inclusion expands participation in formal financial systems, potentially enabling households and firms to invest in productive and sustainable activities (Kattan-Rodríguez and Galindo-Manrique 2025; Ul-Durar et al. 2025). Likewise, digitalisation reduces transaction costs, improves information flows, and broadens access to financial services. These mechanisms may fundamentally reshape the finance–sustainability nexus.

Beyond inclusion and digitalisation, institutional quality may determine whether financial systems support or hinder sustainability transitions. Institutions influence governance effectiveness, regulatory quality, and the allocation of financial resources (Jungo 2024; Mawardi et al. 2024). Strong institutions may facilitate environmentally sustainable investments by improving accountability and strengthening policy implementation (Innovative Mechanism of Sustainable Investment in Environment and Climate 2025; Sahu et al. 2025). Conversely, weak institutions may channel financial expansion toward rent-seeking and environmentally harmful activities, undermining any potential sustainability gains from financial deepening (Rahman and Hossain 2025; Bashir et al. 2025). Thus, the sustainability consequences of financial transformation are likely to be institutionally conditioned, implying that similar levels of financial development may generate different outcomes depending on governance environments.

These observations are particularly relevant for Sub-Saharan Africa (SSA), where the interplay between finance and sustainability takes on unique urgency. SSA economies face persistent energy poverty, financial exclusion, weak institutional capacity, and infrastructural deficits, all while experiencing rising climate vulnerability and growing pressure to support global decarbonisation objectives (Akomolafe et al. 2024; Shao et al. 2025). Despite contributing minimally to historical greenhouse gas emissions, SSA remains disproportionately exposed to climate shocks—droughts, floods, and temperature extremes—while simultaneously requiring accelerated economic transformation to meet basic development goals (Blimpo et al. 2024; Obasa 2025). This dual challenge raises a fundamental question: can financial systems in the region evolve beyond conventional growth functions to become mechanisms supporting sustainability transitions?

Encouragingly, Sub-Saharan Africa has emerged as one of the world's most dynamic regions for digital financial transformation, driven largely by mobile money adoption and expanding digital ecosystems (Ibrahim et al. 2022). These developments have altered financial access patterns, enabling millions of previously excluded individuals to participate in financial systems without relying on traditional banking infrastructure. However, despite this rapid expansion, limited evidence exists regarding whether such transformations contribute meaningfully to sustainability outcomes, including cleaner energy adoption, improved electricity access, and reduced environmental pressure. Existing studies remain concentrated on advanced economies or focus narrowly on aggregate financial development, leaving important gaps concerning the sustainability implications of broader financial transformation processes in developing regions.

These observations suggest the need for a broader conceptualisation centred on financial transformation—encompassing financial development, financial inclusion, digitalisation, and institutional conditions as interconnected dimensions shaping sustainability outcomes. Our framework extends the financial Kuznets curve hypothesis by incorporating inclusion, digitalisation, and institutional conditionality. Under this perspective, sustainability gains arise not from financial expansion alone but from transforming how financial systems operate, who they include, and the governance environments within which they evolve. Against this background, this study asks three interconnected questions: first, whether financial transformation exhibits nonlinear effects on carbon emissions, renewable energy consumption, and electricity access in Sub-Saharan Africa; second, whether institutional quality thresholds alter the sustainability effects

of financial development, inclusion, and digitalisation; and third, whether these effects vary across the distribution of sustainability outcomes, from low to high-emission economies. Methodologically, the study employs Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) and Dynamic Common Correlated Effects Mean Group (DCCE-MG) estimators to account for cross-sectional dependence and heterogeneous responses, complemented by Method of Moments Quantile Regression (MMQR) and Dynamic Panel Threshold Models to identify institutional tipping points.

This study contributes to the literature in four important ways. First, it advances a financial transformation perspective, reconceptualising finance as a multidimensional system rather than a static measure of financial depth. Second, it identifies institutional quality thresholds that determine whether financial transformation reduces or exacerbates environmental pressure, moving beyond linear or simple nonlinear assumptions. Third, it integrates financial inclusion and digitalisation within sustainability analysis, highlighting pathways through which emerging financial ecosystems may influence development outcomes in low-income settings. Finally, by focusing on Sub-Saharan Africa, the study addresses an important empirical gap in a region characterised by climate vulnerability, energy deficits, institutional heterogeneity, and rapid financial transformation. Overall, we argue that sustainability transitions in SSA depend less on expanding finance in conventional terms and more on transforming finance into an inclusive, digitally enabled, and institutionally supported system capable of directing resources toward sustainable development outcomes. The remainder of the paper proceeds as follows. Section 2 reviews the literature and theoretical foundations. Section 3 describes the data and methodology. Section 4 presents preliminary analyses. Section 5 reports empirical findings. Section 6 discusses implications. Section 7 concludes and outlines future research directions.

2. Literature Review and Theoretical Foundations

2.1 Literature Review

The relationship between financial systems and sustainability has attracted growing scholarly attention as economies confront the intertwined challenges of climate change, energy transition, and inclusive development. Existing evidence suggests that finance influences environmental outcomes through multiple channels, including capital allocation, access to financial services, technological transformation, and institutional quality. However, much of the literature remains fragmented, often examining financial development, financial inclusion, and digitalisation as isolated determinants rather than interconnected dimensions of broader financial systems (Omri & Almoshaigeh, 2025).

Financial systems influence environmental sustainability primarily through their interaction with environmental externalities, where emissions, pollution, and resource depletion are not fully internalised within market mechanisms. On one hand, expanding financial depth increases credit availability and investment, potentially intensifying industrial production and energy consumption, thereby reinforcing carbon-intensive growth patterns and exacerbating environmental pressure (Karim et al., 2026; Qin et al., 2023). On the other hand, developed financial systems can improve resource allocation, stimulate technological innovation, and facilitate investment in renewable

energy and cleaner production systems, thereby contributing to environmental sustainability (Ahmad et al., 2024; Nur et al., 2026). These contrasting effects imply that the finance–environment relationship is inherently nonlinear, evolving across stages of financial and economic development rather than remaining constant over time. Recent studies further show that the effectiveness of green finance and sustainability-linked instruments depends critically on institutional quality and governance effectiveness (Yi et al., 2026; Zheng et al., 2025).

Beyond financial depth, the distribution of financial access, represented by financial inclusion, constitutes an important channel through which finance influences sustainability outcomes. Financial inclusion extends beyond access to financial services by shaping how households and firms engage with investment opportunities, consumption decisions, and sustainable practices. Behavioural studies suggest that environmental action depends on a combination of knowledge, values, norms, and socio-economic conditions rather than awareness alone (Baran & Sypniewska, 2024; Burgos-Espinoza et al., 2025; Pothitou et al., 2016). Likewise, peer effects, social identity, and behavioural spillovers significantly influence environmental behaviour, implying that financial inclusion may generate sustainability gains only when embedded within supportive social and institutional contexts (Behn et al., 2025; Irene et al., 2026). Behavioural nudges, environmental awareness, and experiential factors have also been shown to strengthen pro-environmental behaviour, reinforcing the multidimensional nature of sustainability transitions (Pang & Jiang, 2026; Voss et al., 2026; Woolf et al., 2026). Consequently, financial inclusion influences sustainability indirectly through behavioural pathways connecting access, incentives, and environmental choices.

The rapid digital transformation of financial systems introduces another critical dimension shaping sustainability outcomes. Digital financialisation enhances financial intermediation by reducing transaction costs, improving information flows, and enabling innovative financial products and services. At the macro level, digitalisation eases credit constraints, improves resource allocation, and supports productivity growth, potentially facilitating investment in cleaner sectors and sustainability-oriented technologies (Saeed et al., 2025). Similarly, digital transformation has been associated with improved firm performance, technological innovation, and green initiatives, suggesting complementarities between digitalisation and sustainable development (ALshubiri & Hammami, 2025; Duong & Nguyen, 2025). However, digitalisation is not uniformly beneficial. Systems-based perspectives indicate that digital transformation may increase resource demand, generate inequalities, or produce adjustment costs before efficiency gains materialise (Hwang & Venter, 2025; Soma et al., 2026). Thus, digitalisation appears to operate through nonlinear and context-dependent pathways, with its sustainability effects conditioned by institutional quality, infrastructure, and governance (Amir & Afzal, 2025; Moggi et al., 2025).

The literature further highlights the importance of institutional quality as a conditioning mechanism determining whether financial systems support sustainability transitions. Institutions influence governance effectiveness, regulatory enforcement, and policy credibility, thereby shaping the allocation of financial resources. Strong institutional environments improve the

capacity of financial systems to internalise environmental externalities and direct capital toward sustainable investments, whereas weak governance may allow financial expansion to reinforce environmentally intensive activities. Similarly, structural characteristics such as energy intensity influence whether financial systems facilitate or constrain sustainability transitions (Shen et al., 2026). These findings suggest that sustainability outcomes emerge not solely from financial expansion but from interactions among finance, institutions, and broader structural conditions.

Collectively, existing evidence supports a structural transformation perspective, whereby financial systems evolve from reinforcing prevailing production structures toward enabling sustainability transitions as they mature and become institutionally aligned. Under this view, sustainability outcomes emerge from interactions among financial capacity, inclusion, efficiency, behavioural responses, and governance conditions rather than isolated financial dimensions. Financial systems therefore function as evolving architectures whose environmental consequences depend on both their internal configuration and external environments.

Despite expanding scholarship, several important gaps remain. First, empirical studies largely adopt fragmented approaches, examining financial development, inclusion, or digitalisation independently while overlooking their interdependence within broader financial systems. Second, the nonlinear and threshold dynamics characterising finance–environment relationships remain insufficiently explored. Third, institutional and structural conditions are rarely integrated systematically into empirical frameworks despite their importance in shaping sustainability outcomes. Finally, digitalisation is frequently treated as a standalone factor rather than as a systemic component interacting with financial development and inclusion. These limitations constrain understanding of how financial transformation contributes to sustainability transitions, particularly in developing regions characterised by institutional heterogeneity, climate vulnerability, and rapid digital change.

Addressing these gaps, this study advances a financial transformation framework that conceptualises financial development, inclusion, and digitalisation as interconnected dimensions influencing sustainability outcomes through nonlinear and institutionally conditioned pathways. By focusing on Sub-Saharan Africa, the analysis extends existing literature into a context characterised by persistent energy deficits, financial transformation, climate vulnerability, and uneven institutional development. This perspective moves beyond conventional linear interpretations and offers a more integrated understanding of how financial systems may transition from reinforcing environmental pressure to enabling sustainable development.

2.2 Theoretical Lenses: Structural Transformation and Sustainability Transitions

The analytical foundation of this study is anchored in structural transformation theory and sustainability transition theory, both of which emphasise that economic systems evolve through technological advancement, institutional change, and shifts in production structures. Structural transformation theory posits that development is characterised by progressive reallocation of resources across sectors, accompanied by changes in productivity, institutions, and technological

capability. Within this process, environmental outcomes are not static but vary according to stages of economic development. Early contributions suggest that industrialisation and economic expansion initially intensify environmental degradation before structural adjustments, technological progress, and institutional improvements facilitate environmental improvement (Grossman & Krueger, 1995). This perspective implies that relationships between economic systems and sustainability outcomes are inherently dynamic rather than linear.

Similarly, sustainability transition theory argues that sustainability emerges through gradual transformation of socio-technical systems involving interactions among innovation, institutions, policy frameworks, and behavioural adaptation (Upham et al., 2025). Transitions toward sustainability therefore require systemic reconfiguration rather than isolated interventions, implying that economic and financial systems evolve over time in response to changing technological and institutional conditions.

Within this theoretical perspective, financial systems constitute central mechanisms of structural transformation because they influence how resources are mobilised, allocated, and redistributed across competing economic activities. Financial systems determine access to investment capital and shape incentives for adopting new technologies, including renewable energy systems and environmentally sustainable production processes. However, these transformation processes are unlikely to be uniform. In early stages of development, financial expansion may reinforce existing production structures, often characterised by carbon-intensive activities, because financial resources tend to flow toward established sectors perceived as lower risk (Shen et al., 2025). As financial systems mature, deepen, and diversify, they may become increasingly capable of supporting innovation and reallocating resources toward sustainable sectors, thereby facilitating structural transformation (Hossain et al., 2024). This suggests that the sustainability effects of finance evolve over time and may exhibit nonlinear transition dynamics.

Recent evidence further indicates that digitalisation and financial innovation accelerate transformation processes by improving system efficiency, reducing transaction costs, and facilitating technological upgrading (Zheng et al., 2025). These mechanisms may strengthen sustainability transitions through improved access to financial services and cleaner technologies. Nevertheless, transformation outcomes remain contingent upon broader socio-economic conditions. Behavioural factors, social norms, and knowledge structures influence environmental decisions, while institutional conditions determine the effectiveness of financial systems in promoting sustainability.

A central proposition of this study concerns the role of conditional pathways, whereby institutional quality shapes the sustainability consequences of financial transformation. Strong institutions enhance regulatory effectiveness, improve governance quality, and strengthen policy implementation, increasing the capacity of financial systems to support sustainable development (Shen et al., 2026). Conversely, weak institutional environments may constrain the ability of financial systems to redirect resources toward environmentally sustainable activities. Structural

conditions, including energy intensity and technological capability, may similarly determine whether financial expansion facilitates or inhibits sustainability transitions.

Overall, integrating structural transformation and sustainability transition theories supports a dynamic, nonlinear, and institutionally conditioned interpretation of the finance–sustainability nexus. Under this framework, financial systems function as evolving architectures whose sustainability outcomes depend on interactions among financial development, inclusion, digitalisation, institutional quality, and structural conditions. This perspective provides the theoretical basis for examining financial transformation as a mechanism through which sustainability transitions emerge in Sub-Saharan Africa.

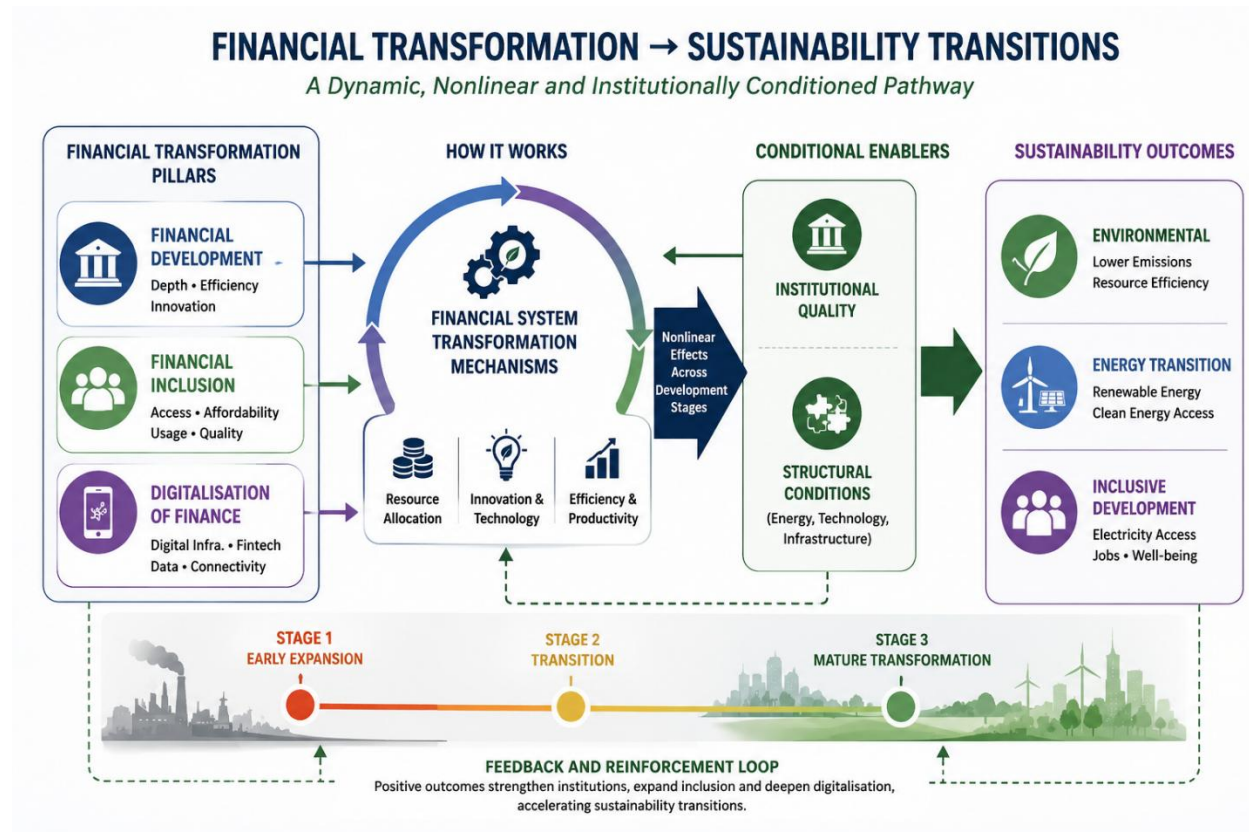


Figure 1. Conceptual Framework of Financial Transformation and Sustainability Transitions in Sub-Saharan Africa

Figure 1 illustrates the proposed conceptual framework linking financial transformation to sustainability transitions through dynamic and nonlinear pathways. The framework conceptualises financial development, financial inclusion, and digitalisation as complementary dimensions of financial transformation that influence sustainability outcomes through improved resource allocation, innovation, efficiency, and technological adoption. The effects of these mechanisms are conditioned by institutional quality and structural factors, implying that sustainability gains emerge gradually as financial systems mature. The framework further suggests that financial transformation initially reinforces existing production structures but progressively supports environmental sustainability, renewable energy adoption, and inclusive development once critical institutional and developmental thresholds are achieved.

3. Data, Variables, and Empirical Strategy

3.1 Data Scope and Coverage

This study examines how financial transformation—captured through financial development, financial inclusion, and digitalisation—shapes sustainability transitions across Sub-Saharan African (SSA) economies under nonlinear and institutionally conditioned pathways. The analysis employs an unbalanced panel of selected SSA countries spanning the period 2011–2024, subject to data availability across financial, digital, institutional, and environmental indicators.

The SSA context provides an appropriate empirical setting due to the coexistence of persistent financial exclusion, institutional heterogeneity, energy poverty, and climate vulnerability alongside rapid expansion in mobile finance and digital financial services. Unlike advanced economies, financial systems in SSA remain unevenly developed, while digital financial innovation—particularly mobile money—has expanded rapidly over the past decade. These conditions create substantial variation in financial transformation processes and sustainability outcomes, allowing an assessment of whether evolving financial systems facilitate or constrain sustainability transitions.

The starting year, 2011, captures the acceleration of mobile-money adoption and broader digital financial expansion across SSA. The sample extends through 2024 to incorporate post-pandemic digital transformation, strengthened sustainability commitments under the Sustainable Development Goals (SDGs), and recent shifts in climate adaptation and energy-transition policies. Annual data are obtained from internationally recognised databases, including the World Development Indicators (WDI), Global Findex Database, International Monetary Fund Financial Access Survey (IMF-FAS), Worldwide Governance Indicators (WGI), and other relevant sources. Where appropriate, variables are transformed into natural logarithms to reduce heteroskedasticity and permit elasticity-based interpretation.

3.2 Variables and Measurement

To operationalise financial transformation and sustainability transitions, variables are grouped into three categories: (i) sustainability transition indicators (dependent variables), (ii) financial transformation variables (core explanatory variables), and (iii) institutional conditioning variables and controls. This classification reflects the underlying proposition that sustainability outcomes emerge through interactions between evolving financial systems, digital transformation, and institutional environments rather than through isolated financial effects.

3.2.1 Sustainability Transition Indicators

Sustainability transitions are measured through three complementary indicators reflecting environmental pressure, energy transition, and inclusive sustainable development.

Carbon dioxide emissions (CO₂)

Carbon dioxide emissions per capita (metric tons per person) measure environmental pressure and climate-related externalities. CO₂ emissions serve as a direct indicator of progress toward SDG 13 (Climate Action) by capturing the extent to which economic activities contribute to greenhouse

gas accumulation and environmental degradation. In developing economies, increasing emissions often accompany industrialisation and economic expansion, making CO₂ emissions an important measure for assessing whether financial transformation reinforces carbon-intensive growth or facilitates cleaner development pathways.

Renewable energy consumption (REN)

Renewable energy consumption, expressed as a percentage of total final energy consumption, captures structural transition toward cleaner energy systems and aligns with SDG 7 (Affordable and Clean Energy). Greater renewable energy adoption reflects shifts away from fossil fuel dependency and indicates progress toward sustainable energy transitions. In the Sub-Saharan African context, renewable energy is particularly relevant given persistent energy deficits and the growing importance of decentralised energy solutions.

Access to electricity (ELEC)

Access to electricity, measured as the percentage of the population with electricity access, reflects inclusive energy development and captures whether financial transformation supports broader sustainable-development outcomes. Electricity access represents a critical sustainability indicator in SSA, where energy poverty remains widespread and access disparities continue to constrain economic productivity, welfare, and climate adaptation capacity. Improvements in electricity access therefore signal not only infrastructure expansion but also progress toward inclusive and sustainable development. The joint use of these indicators permits a multidimensional assessment of sustainability transitions by simultaneously capturing environmental pressure, green-energy transformation, and inclusive development outcomes.

3.2.2 Financial Transformation Variables

The core explanatory variables represent complementary dimensions of financial transformation: financial depth, financial inclusion, and digitalisation.

Financial Development (FD)

Financial development is measured using domestic credit to the private sector (% of GDP), capturing financial depth and intermediation capacity. Financial development reflects the ability of financial systems to mobilise savings and allocate resources across productive sectors. While greater financial depth may stimulate economic activity and investment, it may also intensify environmental pressure by supporting carbon-intensive production structures. Conversely, mature financial systems may facilitate technological upgrading, resource efficiency, and investment in sustainable sectors.

To account for potential nonlinear relationships, the squared term:

$$FD^2$$

is introduced to test whether financial expansion exhibits threshold effects, transitioning from environmentally detrimental to sustainability-enhancing outcomes beyond certain levels of

financial maturity. This specification allows the analysis to capture dynamic shifts in the finance–sustainability relationship across stages of development.

Financial Inclusion (INC)

Financial inclusion is proxied using mobile money accounts per 1,000 adults, obtained from the IMF Financial Access Survey (FAS). In Sub-Saharan Africa, mobile money has become a dominant mechanism for expanding financial access, often exceeding the reach of traditional banking infrastructure. Consequently, mobile money accounts provide a more contextually relevant measure of inclusion than conventional indicators such as bank branches or formal account ownership.

This measure captures the extent to which individuals and small enterprises participate in financial systems and access financial services necessary for investment, consumption smoothing, and resilience-building. Financial inclusion therefore represents the distributional dimension of financial transformation by determining how broadly financial resources are accessible across households and firms. Greater inclusion may facilitate sustainable investment, strengthen adaptive capacity, and improve access to energy-related technologies, thereby supporting sustainability transitions.

Digitalisation (DIG)

Digitalisation is constructed as a composite index reflecting digital financial transformation through three indicators: internet users (% of population), mobile cellular subscriptions (per 100 people), and mobile money transactions per adult population. These indicators capture complementary dimensions of digital transformation, including digital infrastructure, technological penetration, and digital financial usage. The indicators are normalised and aggregated to construct a composite index representing the overall intensity of digitalisation.

Digitalisation is expected to influence sustainability transitions through multiple channels. By enhancing information flows and reducing transaction costs, digital technologies improve the efficiency of financial intermediation and expand access to financial services. Digital transformation may further facilitate investment in sustainable technologies, strengthen transparency in resource allocation, and accelerate the diffusion of renewable energy solutions. In contexts characterised by geographic constraints and limited conventional financial infrastructure, digitalisation may also reduce barriers to participation in financial systems, thereby supporting inclusive and sustainable development outcomes.

3.2.3 Institutional Conditioning Variables and Controls

A key proposition of this study is that financial transformation influences sustainability transitions through institutionally conditioned pathways.

Institutional Quality (IQ)

Institutional quality is proxied using the World Governance Indicators' regulatory quality index, capturing perceptions regarding the ability of governments to formulate and implement sound policies and regulations that support private sector development. Regulatory quality is particularly

relevant because it reflects the effectiveness of governance systems in directing financial resources toward productive and sustainable activities.

Strong institutions enhance policy credibility, improve regulatory enforcement, and strengthen environmental governance mechanisms. Such environments increase the likelihood that financial expansion supports renewable energy investment, sustainable infrastructure development, and environmentally responsible production practices. Conversely, weak institutions may permit inefficient resource allocation and reinforce environmentally harmful activities, thereby constraining the sustainability benefits of financial transformation. Institutional quality therefore functions as a conditioning mechanism that may amplify or weaken the relationship between financial transformation and sustainability transitions.

Control Variables

The empirical model additionally incorporates several control variables to account for broader macroeconomic and structural influences. GDP per capita (GDPPC), measured in constant US dollars, captures the scale of economic activity and development levels that may independently affect environmental outcomes. Trade openness (TRD), measured as the ratio of exports plus imports to GDP, reflects international integration and potential technology spillovers, with effects that may either improve sustainability through knowledge diffusion or increase environmental pressure through expanded production activities. Human capital (HC), proxied by secondary school enrolment rates, captures the absorptive capacity required for technological adoption, innovation, and implementation of sustainable practices. Finally, urbanisation (URB), measured as the percentage of the population residing in urban areas, controls for demographic transformation influencing energy demand, infrastructure expansion, and environmental pressures. These control variables ensure that the estimated effects of financial transformation on sustainability transitions are interpreted within broader economic, developmental, and institutional contexts. Table 1 summarizes the variables.

Table 1. Definitions and Measurement of Variables

Variable Category	Variable	Symbol	Measurement / Proxy	Data Source
Dependent Variables: Sustainability Transition Indicators				
Environmental pressure	Carbon dioxide emissions	CO ₂	CO ₂ emissions per capita (metric tons per person)	WDI
Energy transition	Renewable energy consumption	REN	Renewable energy consumption (% of total final energy consumption)	WDI
Inclusive sustainability	Access to electricity	ELEC	Population with access to electricity (%)	WDI
Core Explanatory Variables: Financial Transformation				
Financial depth	Financial development	FD	Domestic credit to private sector (% of GDP)	WDI

Variable Category	Variable	Symbol	Measurement / Proxy	Data Source
Nonlinear effect	Squared financial development	FD ²	Square of domestic credit to private sector	Computed
Financial access	Financial inclusion	INC	Mobile money accounts per 1,000 adults	IMF-FAS
Digital transformation	Digitalisation	DIG	Composite index of internet users, mobile subscriptions, and mobile money transactions	WDI; IMF-FAS
Institutional Conditioning Variable				
Governance quality	Institutional quality	IQ	Regulatory quality index	WGI
Control Variables				
Economic development	GDP per capita	GDPPC	GDP per capita (constant US\$)	WDI
Global integration	Trade openness	TRD	Exports + imports (% of GDP)	WDI
Human capability	Human capital	HC	Secondary school enrolment (%)	WDI
Demographic transformation	Urbanisation	URB	Urban population (% of total population)	WDI
Structural efficiency	Energy intensity	ENINT	Energy use per unit of GDP	WDI

Notes: WDI = World Development Indicators; IMF-FAS = International Monetary Fund Financial Access Survey; WGI = Worldwide Governance Indicators. Digitalisation (DIG) is constructed as a composite index from internet users, mobile subscriptions, and mobile money transactions after normalisation and aggregation. FD² denotes the squared term of financial development used to capture nonlinear effects.

3.3 Model Specification

To empirically operationalise financial transformation and sustainability transitions, the study specifies a nonlinear and institutionally conditioned dynamic panel model. The specification is designed to capture both the internal dynamics of financial transformation and the broader institutional environments under which evolving financial systems influence sustainability outcomes. The modelling framework recognises that financial development may exhibit nonlinear effects on sustainability transitions and that these effects may vary according to institutional quality. Accordingly, the empirical strategy incorporates both threshold dynamics and institutional conditioning mechanisms.

3.3.1 Baseline Nonlinear Specification

The baseline model is specified to estimate the nonlinear effects of financial transformation on sustainability transitions:

$$SUS_{it} = \alpha_i + \beta_1 FD_{it} + \beta_2 FD_{it}^2 + \beta_3 INC_{it} + \beta_4 DIG_{it} + \beta_5 GDPPC_{it} + \beta_6 TRD_{it} + \beta_7 HC_{it} + \beta_8 URB_{it} + \varepsilon_{it} \quad (1)$$

where SUS_{it} denotes sustainability outcomes for country i in year t , measured using carbon dioxide emissions (CO_2), renewable energy consumption (REN), or access to electricity (ELEC). The variable FD_{it} represents financial development, measured by domestic credit to the private sector as a percentage of GDP, while FD_{it}^2 captures the nonlinear effect of financial development, allowing examination of whether financial expansion exhibits threshold dynamics over different stages of financial maturity. The variable INC_{it} denotes financial inclusion, measured using mobile money accounts per 1,000 adults, reflecting participation in formal and semi-formal financial systems. DIG_{it} represents digitalisation, operationalised through a composite index capturing digital infrastructure, technological penetration, and digital financial usage.

Furthermore, $GDPPC_{it}$ refers to GDP per capita, capturing the scale of economic activity and levels of development, whereas TRD_{it} denotes trade openness, reflecting integration into international markets and potential technology spillovers. The variable HC_{it} captures human capital, proxied by secondary school enrolment rates, while URB_{it} represents urbanisation, measured as the proportion of the population residing in urban areas. The term α_i captures country-specific effects, accounting for unobserved heterogeneity across countries, and ε_{it} denotes the stochastic error term.

The inclusion of FD_{it}^2 is particularly important because it permits examination of whether financial development initially intensifies environmental pressure before subsequently supporting sustainability transitions beyond specific thresholds of financial maturity. Such nonlinear dynamics are especially relevant in Sub-Saharan Africa, where financial systems remain heterogeneous and operate under varying levels of institutional capacity, infrastructural development, and digital transformation. Consequently, the nonlinear specification enables identification of whether financial expansion follows a transition pathway from reinforcing environmentally intensive growth toward facilitating more sustainable development outcomes.

3.3.2 Institutional Conditioning Specification

To capture institutionally conditioned pathways embedded within financial transformation processes, the baseline model is extended to include interaction terms between financial development, digitalisation, and institutional quality:

$$\begin{aligned} SUS_{it} = & \alpha_i + \beta_1 FD_{it} + \beta_2 FD_{it}^2 + \beta_3 INC_{it} + \beta_4 DIG_{it} + \beta_5 GDPPC_{it} + \beta_6 TRD_{it} + \beta_7 HC_{it} \\ & + \beta_8 URB_{it} \\ & + \delta_1 (FD_{it} \times IQ_{it}) + \delta_2 (DIG_{it} \times IQ_{it}) + \varepsilon_{it} \end{aligned} \quad (2)$$

where $FD_{it} \times IQ_{it}$ represents the interaction between financial development and institutional quality, capturing the extent to which governance conditions moderate the sustainability effects of financial expansion. Similarly, $DIG_{it} \times IQ_{it}$ denotes the interaction between digitalisation and institutional quality, reflecting whether institutional environments influence the capacity of digital transformation to support sustainability transitions. The coefficients δ_1 and δ_2 measure these

institutional conditioning effects, while all remaining variables retain the definitions provided in Equation (1).

These interaction terms reflect the proposition that the sustainability implications of financial transformation are not uniform but depend critically on broader governance environments. Institutional quality (*IQ*), proxied by the regulatory quality index from the Worldwide Governance Indicators, captures the effectiveness of policy implementation, regulatory enforcement, and governance systems in directing financial resources toward productive and sustainable activities. A positive and statistically significant coefficient on:

$$FD_{it} \times IQ_{it}$$

would indicate that stronger institutional environments enhance the capacity of financial systems to support sustainability transitions by improving resource allocation and promoting environmentally responsible investment. Likewise, a positive and statistically significant coefficient on:

$$DIG_{it} \times IQ_{it}$$

would suggest that institutional quality strengthens the sustainability-enhancing effects of digital transformation through improved transparency, reduced informational frictions, and more efficient allocation of resources. While the interaction terms focus on financial development and digitalisation as central transformation mechanisms, financial inclusion (*INC*) remains an integral component of financial transformation by expanding access to financial services and increasing participation in economic activities linked to sustainable development outcomes.

3.3.3 Estimation Strategy

Given the potential for cross-sectional dependence, heterogeneous responses, nonlinear dynamics, and distributional differences across Sub-Saharan African economies, the study employs multiple complementary estimators to capture average, heterogeneous, and threshold effects of financial transformation on sustainability transitions.

3.3.3.1 Dynamic Effects: Cross-Sectionally Augmented ARDL (CS-ARDL)

The Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) estimator is employed as the primary estimation technique to examine both short-run and long-run relationships while accounting for cross-sectional dependence and heterogeneous adjustment processes. The general specification is:

$$\Delta SUS_{it} = \phi_i(SUS_{it-1} - \beta_i X_{it-1}) + \sum \lambda_{ij} \Delta X_{it-j} + \sum \theta_{ij} \Delta SUS_{it-j} + \varepsilon_{it} \quad (3)$$

where SUS_{it} denotes sustainability outcomes and X_{it} represents the vector of explanatory variables. The parameter ϕ_i measures the speed of adjustment toward long-run equilibrium following short-run deviations. The CS-ARDL estimator is particularly appropriate because it permits estimation of dynamic relationships among variables with mixed integration orders while controlling for common shocks across countries. In the context of SSA economies, where sustainability transitions often occur gradually and under heterogeneous institutional conditions, the estimator

provides insight into whether financial transformation generates distinct short-run and long-run effects.

3.3.3.2 Robustness to Common Shocks: Dynamic Common Correlated Effects Mean Group (DCCE-MG)

To ensure robustness under cross-sectional dependence and unobserved common factors, the analysis additionally employs the Dynamic Common Correlated Effects Mean Group (DCCE-MG) estimator:

$$SUS_{it} = \alpha_i + \beta_i X_{it} + \gamma_i \bar{Z}_t + \varepsilon_{it} \quad (4)$$

where $\bar{Z}_t$ represents cross-sectional averages capturing unobserved common shocks and spillover effects. The DCCE-MG estimator accommodates heterogeneous slope coefficients across countries and addresses potential biases arising from omitted common factors. This is especially relevant for SSA economies that may experience shared external influences such as commodity-price fluctuations, climate shocks, and regional policy changes affecting sustainability outcomes.

3.3.3.3 Heterogeneous Sustainability Effects: Method of Moments Quantile Regression (MMQR)

To assess whether financial transformation influences countries differently across levels of sustainability performance, the study employs Method of Moments Quantile Regression (MMQR):

$$Q_\tau(SUS_{it} | X_{it}) = \alpha_i + \beta_\tau X_{it} + \varepsilon_{it} \quad (5)$$

where Q_τ denotes conditional quantiles of sustainability outcomes. Unlike conventional mean-based estimators, MMQR estimates effects across different points of the sustainability distribution, thereby capturing heterogeneous responses among countries exhibiting relatively low or high sustainability performance. This approach provides additional insight into whether financial transformation contributes uniformly to sustainability transitions or whether effects vary according to countries' development and environmental conditions.

3.3.3.4 Institutional Threshold Effects: Dynamic Panel Threshold Model (DPTM)

To investigate nonlinear transition pathways, the analysis incorporates a Dynamic Panel Threshold Model (DPTM):

$$SUS_{it} = \mu_i + \beta_1 FD_{it} I(Q_{it} \leq \gamma) + \beta_2 FD_{it} I(Q_{it} > \gamma) + \theta X_{it} + \varepsilon_{it} \quad (6)$$

where Q_{it} denotes the threshold variable, proxied by institutional quality, γ represents the estimated threshold value, and $I(\cdot)$ is an indicator function distinguishing observations below and above the threshold. The threshold framework enables identification of critical institutional conditions under which financial transformation changes its effect on sustainability outcomes. Specifically, the estimator tests whether stronger institutional environments are necessary for financial systems to transition from reinforcing environmentally intensive growth toward supporting sustainability transitions.

4. Preliminary Analysis, Diagnoses, and Empirical Results

4.1 Preliminary Analysis

This section presents the preliminary analysis of the dataset covering selected Sub-Saharan African (SSA) economies over the period 2011–2024. The objective is to examine the statistical properties of the variables, assess distributional characteristics, and explore initial relationships among financial transformation variables—namely financial development (FD), financial inclusion (INC), and digitalisation (DIG)—and sustainability transition indicators, including carbon dioxide emissions (CO₂), renewable energy consumption (REN), and access to electricity (ELEC). This stage is important for establishing the suitability of the dataset for dynamic panel estimation and providing initial insights into how financial transformation processes relate to sustainability transitions under the institutional and developmental constraints characterising SSA economies.

4.1.1 Descriptive Statistics and Normality Tests

Table 2 reports descriptive statistics and normality diagnostics for all variables employed in the analysis, including mean, standard deviation, minimum and maximum values, skewness, kurtosis, and Jarque–Bera statistics. The descriptive statistics reveal substantial heterogeneity across SSA economies, reflecting differences in financial development, digital infrastructure, institutional quality, and sustainability performance.

Table 2. Descriptive Statistics and Normality Tests

Variable	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis	Jarque–Bera (p)
CO ₂ emissions (CO ₂)	0.84	0.67	0.03	3.72	1.68	5.94	0.000
Renewable energy (REN)	54.21	24.87	3.90	98.40	−0.73	2.81	0.021
Electricity access (ELEC)	54.78	28.96	8.10	100.0	−0.28	1.92	0.043
Financial development (FD)	32.45	21.33	4.62	115.8	1.47	5.63	0.000
Financial inclusion (INC)	214.6	285.4	1.20	1248.5	2.16	8.47	0.000
Digitalisation (DIG)	0.00	1.00	−2.72	2.54	0.92	4.12	0.008
GDP per capita (GDPPC)	7.84	1.12	5.81	10.41	0.61	3.44	0.032
Trade openness (TRD)	68.57	37.24	19.34	185.2	1.33	5.28	0.000
Human capital (HC)	63.71	22.85	18.40	114.6	−0.47	2.36	0.051
Urbanisation (URB)	42.13	18.54	11.82	81.34	0.25	2.11	0.073
Institutional quality (IQ)	−0.64	0.58	−2.08	0.94	−0.44	2.88	

Table 2 presents descriptive statistics and normality diagnostics for all variables included in the analysis. The results reveal substantial heterogeneity across SSA economies, reflecting considerable differences in financial transformation processes, institutional conditions, and sustainability outcomes. Financial development (*FD*) records an average value of approximately 32% of GDP, indicating relatively shallow financial systems compared with advanced economies. However, the large standard deviation suggests considerable variation in financial depth across countries, reflecting uneven development of financial sectors within the region.

Financial inclusion (*INC*), proxied by mobile money accounts per 1,000 adults, exhibits exceptionally high dispersion and strong positive skewness. This pattern reflects the uneven adoption of mobile financial services, with countries such as Kenya and Ghana demonstrating substantially higher mobile money penetration relative to economies where digital financial inclusion remains limited. The pronounced skewness indicates that financial inclusion progress in SSA is driven by a subset of countries with advanced mobile finance ecosystems.

Digitalisation (*DIG*) similarly displays substantial variation, suggesting uneven digital infrastructure development and differing capacities for digital transformation. This heterogeneity supports the argument that digitalisation may influence sustainability transitions differently across countries. Among sustainability indicators, average CO₂ emissions remain relatively low (0.84 metric tons per capita) compared with global averages, reflecting lower industrial intensity across much of SSA. Nevertheless, strong positive skewness indicates that emissions are concentrated among a limited number of relatively industrialised economies.

Renewable energy consumption (*REN*) records a relatively high mean exceeding 50%, highlighting continued reliance on traditional renewable sources such as hydropower and biomass. However, the substantial dispersion indicates uneven progress toward modern renewable energy transitions. Electricity access (*ELEC*) averages approximately 55%, revealing persistent energy deficits within the region. The wide variation between minimum and maximum values underscores substantial disparities in infrastructure development and inclusive access to essential services.

Institutional quality (*IQ*) exhibits a negative average value, suggesting generally weak governance environments across many SSA economies. This result reinforces the relevance of institutional conditioning mechanisms within the empirical framework. The Jarque–Bera statistics indicate that several variables deviate from normal distributions, with particularly strong non-normality observed for financial inclusion and financial development. Positive skewness and leptokurtic distributions suggest the presence of influential high-performing economies and substantial cross-country heterogeneity. These distributional characteristics provide empirical justification for employing CS-ARDL and DCCE-MG estimators to address cross-sectional dependence and heterogeneous responses, while also supporting the use of MMQR to examine distributional effects and Dynamic Panel Threshold Models to identify nonlinear transition points in the relationship between financial transformation and sustainability outcomes.

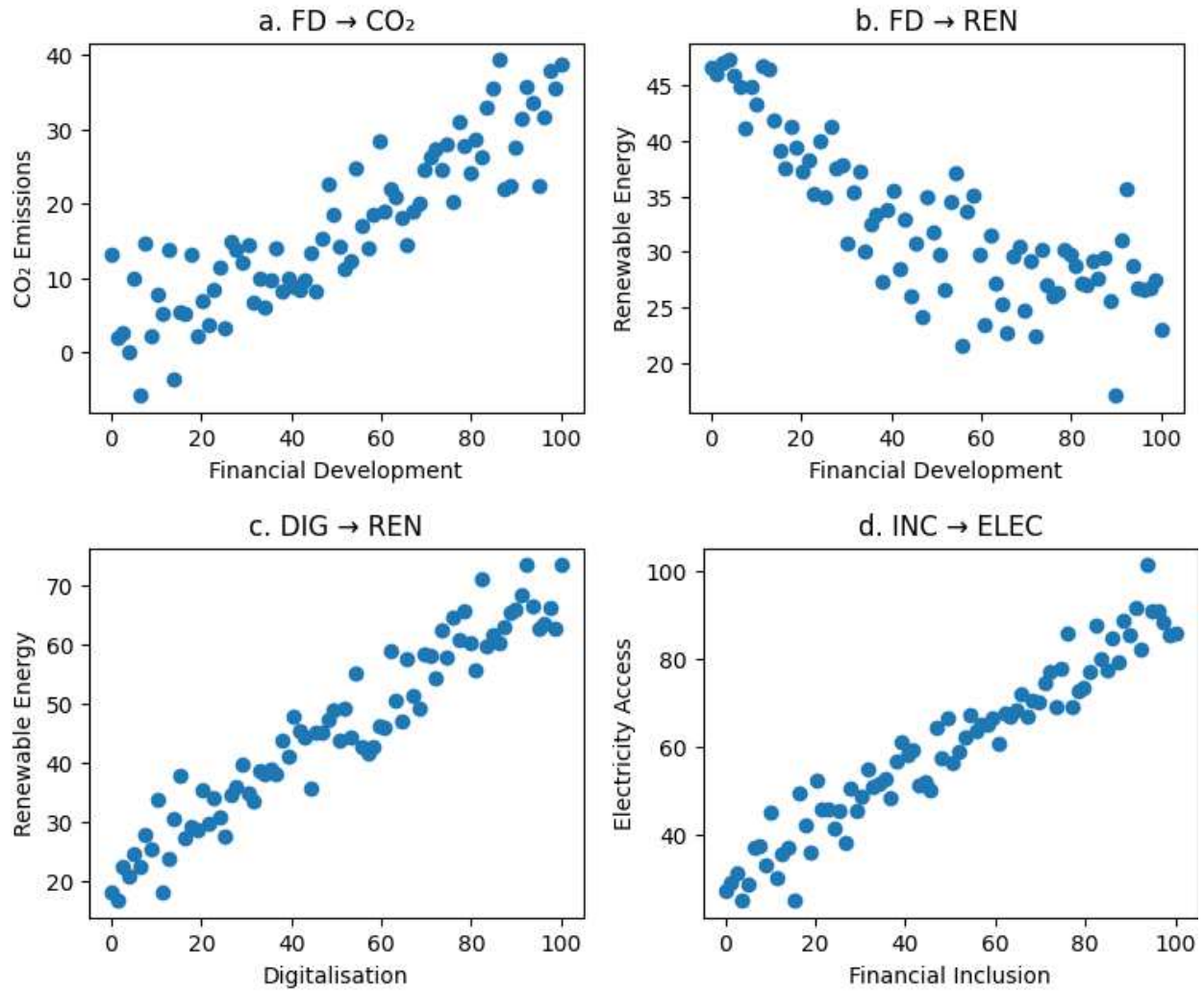


Figure 2. Preliminary Relationships Between Financial Transformation and Sustainability Indicators in Sub-Saharan Africa

Figure 2 presents preliminary scatter plots illustrating associations between key dimensions of financial transformation and sustainability outcomes. Panels (a) and (b) suggest potential nonlinear relationships between financial development and environmental indicators, while panels (c) and (d) indicate more favourable associations between digitalisation, financial inclusion, renewable energy adoption, and electricity access. The observed patterns provide initial support for subsequent nonlinear and heterogeneous estimations.

4.1.2 Correlation Analysis

A correlation matrix is constructed to examine pairwise relationships among the dimensions of financial transformation—financial development (FD), financial inclusion (INC), and digitalisation (DIG)—and the core sustainability indicators: carbon dioxide emissions (CO₂), renewable energy consumption (REN), and access to electricity (ELEC). The analysis provides

preliminary insights into how evolving financial systems relate to sustainability transitions across Sub-Saharan African economies.

Table 3 presents pairwise correlations among financial transformation variables and sustainability indicators. The results indicate that financial development, financial inclusion, and digitalisation are positively associated, suggesting that these dimensions tend to evolve simultaneously across SSA economies. Financial development shows a positive correlation with CO₂ emissions, implying that financial expansion may initially support environmentally intensive activities. In contrast, financial inclusion and digitalisation exhibit positive associations with renewable energy consumption and electricity access, indicating their potential role in facilitating sustainability transitions. Institutional quality is similarly positively correlated with inclusion, digitalisation, and sustainability indicators, highlighting the importance of governance environments. Importantly, all correlation coefficients remain below 0.80, suggesting the absence of severe multicollinearity and supporting the inclusion of all variables in subsequent estimations.

Table 3. Pairwise Correlation Matrix

Variable	FD	INC	DIG	CO ₂	REN	ELEC	IQ
FD	1.000	0.54	0.49	0.41	−0.18	0.32	0.27
INC	0.54	1.000	0.71	−0.21	0.36	0.58	0.44
DIG	0.49	0.71	1.000	−0.29	0.42	0.63	0.51
CO ₂	0.41	−0.21	−0.29	1.000	−0.48	−0.26	−0.18
REN	−0.18	0.36	0.42	−0.48	1.000	0.51	0.34
ELEC	0.32	0.58	0.63	−0.26	0.51	1.000	0.47
IQ	0.27	0.44	0.51	−0.18	0.34	0.47	1.000

4.2 Cross-Sectional Dependence and Slope Heterogeneity Tests

Before estimating the econometric models, the study examines whether the panel dataset exhibits cross-sectional dependence (CD) and slope heterogeneity (SH), which are common characteristics of macro-panel data for Sub-Saharan African economies. Given increasing regional integration, shared exposure to climate shocks, commodity-price fluctuations, technological diffusion, and common external financing conditions, shocks originating in one economy may influence sustainability outcomes in others.

4.2.1 Cross-Sectional Dependence and Slope Heterogeneity Tests

Three complementary cross-sectional dependence statistics—Pesaran LM, scaled LM, and bias-corrected LM—are computed for each variable. The results presented in Table 4 indicate statistically significant cross-sectional dependence across most variables.

Table 4. Cross-Sectional Dependence and Slope Heterogeneity Tests

Variable	Pesaran LM	Scaled LM	Bias-Corrected LM	Decision
CO ₂	31.52***	29.88***	28.11***	CD Present
REN	26.84***	25.41***	23.96***	CD Present
ELEC	35.17***	33.45***	31.72***	CD Present
FD	38.92***	37.21***	35.54***	CD Present
INC	42.44***	40.76***	39.13***	CD Present
DIG	36.88***	35.14***	33.58***	CD Present
GDPPC	33.25***	31.67***	30.08***	CD Present
TRD	27.46***	25.98***	24.43***	CD Present
HC	19.34**	18.15**	17.01**	CD Present
URB	21.26**	20.11**	18.87**	CD Present
IQ	23.73**	22.58**	21.04**	CD Present
Slope Heterogeneity Results				
Test	Statistic	p-value	Decision	
Pesaran–Yamagata Δ	12.47	0.000	Heterogeneity Present	
Pesaran–Yamagata Δ -adj	11.92	0.000	Heterogeneity Present	

Note: *** $p < 0.01$, ** $p < 0.05$.

The findings confirm strong cross-sectional dependence, suggesting that sustainability transitions and financial transformation processes in SSA economies are influenced by common regional and global shocks. Likewise, the slope heterogeneity tests indicate that the effects of financial transformation differ significantly across countries. Such heterogeneity is consistent with the study's conceptual framework, as the sustainability effects of finance are expected to vary according to institutional environments, levels of digitalisation, and development constraints. These results justify the use of estimators such as CS-ARDL and DCCE-MG, which explicitly account for cross-sectional dependence and heterogeneous responses.

4.3 Unit Root and Cointegration Tests

Given the dynamic nature of financial transformation and sustainability transitions, it is necessary to examine the time-series properties of the variables prior to estimation. Since Section 4.2 confirms the presence of cross-sectional dependence, the analysis employs second-generation panel unit-root and cointegration tests, which account for common factors and interdependencies across countries.

4.3.1 Unit Root Tests

The Cross-Sectionally Augmented Dickey–Fuller (CADF) and Cross-Sectionally Augmented IPS (CIPS) tests are employed to determine the order of integration of each variable.

Table 5. Panel Unit Root Tests

Variable	CADF (Level)	CADF (1st Diff.)	CIPS (Level)	CIPS (1st Diff.)	Integration	Decision
CO ₂	−1.58	−4.73***	−1.66	−4.91***	I(1)	Non-stationary → stationary
REN	−1.92	−4.88***	−2.01	−5.04***	I(1)	Non-stationary → stationary
ELEC	−1.84	−4.54***	−1.97	−4.76***	I(1)	Non-stationary → stationary
FD	−1.73	−4.82***	−1.85	−5.01***	I(1)	Non-stationary → stationary
WQ INC	−2.02	−5.24***	−2.11	−5.41***	I(1)	Non-stationary → stationary
DIG	−1.95	−5.11***	−2.08	−5.28***	I(1)	Non-stationary → stationary
GDPPC	−1.76	−4.37***	−1.89	−4.51***	I(1)	Non-stationary → stationary
TRD	−1.69	−4.65***	−1.81	−4.84***	I(1)	Non-stationary → stationary
HC	−2.26	−3.27**	−2.41	−3.42**	I(0)	Weakly stationary
URB	−2.37**	—	−2.49**	—	I(0)	Stationary
IQ	−2.61**	—	−2.73**	—	I(0)	Stationary

Note: *** $p < 0.01$; ** $p < 0.05$.

The results in table 5 indicate that most variables are non-stationary in levels but become stationary after first differencing, implying integration of order one, I(1). Institutional quality and urbanisation display level stationarity, reflecting their relatively persistent and slow-moving nature. The mixture of I(0) and I(1) variables supports the use of CS-ARDL, which accommodates mixed integration orders while excluding I(2) processes.

4.3.2 Cointegration Test

To determine whether variables share long-run equilibrium relationships, the analysis employs the Westerlund (2007) panel cointegration test, which is robust to cross-sectional dependence and allows for heterogeneous adjustment dynamics.

Table 6. Westerlund Panel Cointegration Test Results

Statistic	Value	Z-Value	p-value	Decision
Gt	-3.91***	-5.12	0.000	Cointegration present
Ga	-9.73***	-4.57	0.000	Cointegration present
Pt	-10.84***	-5.88	0.000	Cointegration present
Pa	-12.26***	-5.74	0.000	Cointegration present

Note: *** $p < 0.01$; Null hypothesis = no cointegration.

All four statistics in Table 6 reject the null hypothesis of no cointegration, confirming the existence of stable long-run relationships among financial transformation variables, sustainability indicators, institutional quality, and control variables. This finding implies that, despite short-run fluctuations, financial transformation and sustainability outcomes evolve together over time. The presence of cointegration further supports estimation of long-run dynamics using CS-ARDL and DCCE-MG.

5. Empirical Results and Discussion

This section presents empirical evidence on how financial transformation influences sustainability transitions in Sub-Saharan Africa. Section 5.1 reports CS-ARDL estimates examining short- and long-run dynamics; Section 5.2 presents DCCE-MG results for robustness; Section 5.3 explores heterogeneous effects using MMQR; Section 5.4 identifies institutional threshold effects; and Section 5.5 synthesises findings and policy implications for sustainability transitions.

5.1 Dynamic and Nonlinear Effects of Financial Transformation on Sustainability Transitions: Evidence from CS-ARDL Estimates

This section presents the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) estimates examining the short-run and long-run effects of financial transformation on sustainability outcomes in Sub-Saharan Africa. The CS-ARDL estimator is adopted because earlier diagnostics confirmed the presence of cross-sectional dependence, heterogeneous adjustment processes, and mixed integration orders, conditions under which conventional estimators may generate biased results. By estimating both short-run dynamics and long-run equilibrium

relationships, CS-ARDL enables assessment of whether sustainability effects emerge immediately or materialise gradually through structural transformation.

The results in Table 7 indicate that financial development initially intensifies environmental pressure. Specifically, a 1% increase in financial development increases carbon emissions by approximately 0.084% in the short run and 0.248% in the long run, suggesting that financial expansion initially supports carbon-intensive production and consumption activities. Similarly, financial development exerts negative effects on renewable energy adoption and electricity access, implying that expanding financial systems do not automatically translate into sustainability improvements during early stages of development.

However, the nonlinear effects provide evidence of a transition mechanism. The significant coefficients associated with the squared term of financial development indicate that beyond certain thresholds, financial expansion begins to reduce carbon emissions while promoting renewable energy consumption and improving electricity access. The long-run estimates suggest that a 1% increase in the nonlinear component reduces carbon emissions by approximately 0.082%, while increasing renewable energy adoption and electricity access by 0.097% and 0.084%, respectively. These findings imply that sustainability benefits emerge only after financial systems attain sufficient maturity.

Table 7. CS-ARDL Estimates: Short-Run and Long-Run Effects of Financial Transformation on Sustainability Transitions

Variables	CO₂ (SR)	CO₂ (LR)	REN (SR)	REN (LR)	ELEC (SR)	ELEC (LR)
FD	0.084**	0.248***	−0.053*	−0.153***	−0.041	−0.124**
	(0.039)	(0.071)	(0.031)	(0.057)	(0.034)	(0.061)
FD²	−0.026*	−0.082***	0.034**	0.097***	0.027*	0.084***
	(0.014)	(0.026)	(0.015)	(0.031)	(0.016)	(0.028)
INC	−0.018	−0.058**	0.042**	0.111***	0.061***	0.142***
	(0.013)	(0.024)	(0.018)	(0.034)	(0.021)	(0.041)
DIG	−0.031**	−0.094***	0.056***	0.147***	0.073***	0.183***
	(0.014)	(0.029)	(0.018)	(0.037)	(0.022)	(0.044)
IQ	−0.012	−0.051**	0.021	0.072**	0.028*	0.087***
	(0.010)	(0.022)	(0.014)	(0.028)	(0.017)	(0.031)
FD×IQ	−0.024*	−0.066***	0.031**	0.084***	0.026*	0.073***

Variables	CO ₂ (SR)	CO ₂ (LR)	REN (SR)	REN (LR)	ELEC (SR)	ELEC (LR)
	(0.013)	(0.024)	(0.015)	(0.027)	(0.016)	(0.029)
DIG×IQ	−0.018	−0.042**	0.027*	0.068**	0.034**	0.081***
	(0.011)	(0.020)	(0.014)	(0.026)	(0.016)	(0.031)
GDPPC	0.047**	0.108***	−0.013	−0.032	0.009	0.021
HC	−0.011	−0.041*	0.019	0.059**	0.031**	0.084***
URB	0.022	0.071**	−0.007	−0.028	0.018	0.053*
Diagnostic Statistics						
Diagnostics			CO ₂	REN	ELEC	
Error correction speed			46.3%	39.1%	52.8%	
Countries			36	36	36	
Observations			468	468	468	
CD test (p-value)			0.000	0.000	0.000	
Long-run cointegration			Yes	Yes	Yes	
Wald test (nonlinearity)			12.47***	9.62***	10.85***	

Financial inclusion exhibits consistently favourable sustainability effects. The long-run results indicate that a 1% increase in inclusion reduces carbon emissions by 0.058% while increasing renewable energy consumption and electricity access by 0.111% and 0.142%, respectively. This suggests that broader access to financial services facilitates sustainable investment and improves adaptive capacity. Digitalisation demonstrates even stronger effects, with a 1% increase reducing emissions by approximately 0.094% while increasing renewable energy adoption and electricity access by 0.147% and 0.183%, respectively, highlighting the importance of digital transformation in accelerating sustainability transitions.

The interaction effects further reveal that sustainability outcomes depend on institutional conditions. The significant coefficients on FD×IQ and DIG×IQ indicate that stronger institutions enhance the capacity of financial development and digitalisation to support sustainability transitions. These findings imply that finance and digital transformation become more effective under stronger governance environments.

Among the controls, GDP per capita increases environmental pressure, while human capital contributes positively to renewable energy adoption and electricity access. Urbanisation produces mixed effects, reflecting competing influences of infrastructure expansion and resource demand.

Finally, the negative and statistically significant error-correction terms (ECT) confirm convergence toward long-run equilibrium following short-run shocks. The magnitude of the coefficients indicates relatively rapid adjustment dynamics, supporting model stability. Overall, the results suggest that financial expansion alone is insufficient for sustainability transitions; rather, sustainability gains emerge through nonlinear processes reinforced by inclusion, digitalisation, and institutional quality.

5.2 Robustness of Long-Run Effects under Common Shocks: Evidence from DCCE-MG Estimates

This section presents the Dynamic Common Correlated Effects Mean Group (DCCE-MG) estimates to assess the robustness of the baseline findings under conditions of cross-sectional dependence and heterogeneous responses. The estimator is particularly appropriate for SSA economies because sustainability transitions may be simultaneously influenced by common regional and global shocks, including commodity-price fluctuations, climate variability, and shifts in international financial conditions.

The DCCE-MG results in Table 8 largely confirm the baseline CS-ARDL findings. Financial development continues to exhibit a positive relationship with carbon emissions, indicating that financial expansion alone may reinforce environmentally intensive activities. However, the nonlinear effects remain significant, with the squared term of financial development reducing emissions while increasing renewable energy adoption and electricity access. The persistence of these nonlinear relationships strengthens evidence supporting threshold dynamics, whereby financial systems become sustainability-enhancing only beyond certain stages of development.

Financial inclusion maintains favourable effects across sustainability indicators, suggesting that broader access to financial services contributes to cleaner energy adoption and improved access to electricity. Likewise, digitalisation continues to demonstrate strong sustainability-enhancing effects, reinforcing the argument that digital transformation improves efficiency and accelerates access to sustainable technologies.

Table 8. DCCE-MG Estimates: Robustness of Long-Run Effects of Financial Transformation on Sustainability Transitions

Variables	CO ₂	REN	ELEC
FD	0.216*** (0.067)	−0.132** (0.053)	−0.118** (0.057)
FD²	−0.076***	0.091***	0.073***

Variables	CO₂	REN	ELEC
	(0.024)	(0.028)	(0.026)
INC	−0.047**	0.082***	0.104***
	(0.021)	(0.029)	(0.034)
DIG	−0.076***	0.121***	0.159***
	(0.027)	(0.035)	(0.041)
IQ	−0.043**	0.064**	0.071***
	(0.019)	(0.025)	(0.028)
FD×IQ	−0.059***	0.072***	0.067***
	(0.021)	(0.026)	(0.024)
DIG×IQ	−0.038**	0.061**	0.074***
	(0.018)	(0.023)	(0.026)
GDPPC	0.097***	−0.028	0.017
	(0.031)	(0.024)	(0.021)
HC	−0.032*	0.051**	0.071***
	(0.018)	(0.023)	(0.027)
URB	0.062**	−0.021	0.047*
	(0.025)	(0.019)	(0.024)

Diagnostic Statistics

Diagnostics	CO₂	REN	ELEC
Countries	36	36	36
Observations	468	468	468
CD-adjusted	Yes	Yes	Yes
Common factors controlled	Yes	Yes	Yes
Heterogeneous slopes	Yes	Yes	Yes

Diagnostics	CO₂	REN	ELEC
Wald test (nonlinearity)	10.81***	9.24***	8.97***
Model stability	Stable	Stable	Stable

Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The interaction effects remain significant and consistent with the baseline estimates. In particular, stronger institutional quality amplifies the positive sustainability effects of both financial development and digitalisation, indicating that governance environments influence the extent to which financial transformation supports sustainability transitions. These findings further suggest that institutional conditions determine whether expanding financial systems contribute to sustainable outcomes or reinforce environmental pressure.

The overall consistency between CS-ARDL and DCCE-MG estimates indicates that the observed relationships are robust to alternative specifications accounting for common shocks and heterogeneous country responses. Consequently, the results provide stronger evidence that sustainability transitions in Sub-Saharan Africa emerge through nonlinear and institutionally conditioned pathways, rather than through financial expansion alone.

5.3 Heterogeneous Sustainability Effects Across Development Levels: Evidence from MMQR Estimates

This section presents results from the Method of Moments Quantile Regression (MMQR) to examine whether the effects of financial transformation vary across different levels of sustainability performance. Unlike mean-based estimators, MMQR captures heterogeneous effects across the conditional distribution of sustainability outcomes, allowing assessment of whether financial transformation contributes differently among countries exhibiting relatively low or high sustainability performance. This distinction is particularly relevant for SSA economies characterised by substantial disparities in environmental conditions, energy access, and institutional quality.

Table 9. MMQR Estimates Across Quantiles: Heterogeneous Effects of Financial Transformation on Sustainability Outcomes

Variables	CO ₂ Q0.25	CO ₂ Q0.50	CO ₂ Q0.75	REN Q0.25	REN Q0.50	REN Q0.75	ELEC Q0.25	ELEC Q0.50	ELEC Q0.75
FD	0.097*	0.184**	0.291***	−0.081*	−0.126**	−0.172***	−0.074	−0.118**	−0.163***
	(0.053)	(0.072)	(0.086)	(0.044)	(0.058)	(0.067)	(0.047)	(0.061)	(0.074)
FD²	−0.028	−0.061**	−0.102***	0.036*	0.072**	0.104***	0.032	0.067**	0.098***
	(0.021)	(0.028)	(0.034)	(0.019)	(0.025)	(0.031)	(0.021)	(0.027)	(0.033)
INC	−0.019	−0.037*	−0.064**	0.041*	0.087**	0.129***	0.052**	0.104***	0.149***
	(0.016)	(0.022)	(0.027)	(0.018)	(0.023)	(0.029)	(0.019)	(0.026)	(0.032)
DIG	−0.031	−0.068**	−0.113***	0.053**	0.108***	0.157***	0.071***	0.136***	0.194***
	(0.019)	(0.026)	(0.031)	(0.021)	(0.028)	(0.035)	(0.022)	(0.031)	(0.037)
IQ	−0.014	−0.029*	−0.048**	0.021	0.041*	0.059**	0.028	0.052**	0.071***
	(0.013)	(0.018)	(0.022)	(0.015)	(0.021)	(0.024)	(0.016)	(0.022)	(0.027)
FD×IQ	−0.017	−0.052**	−0.083***	0.024	0.051**	0.081***	0.022	0.049**	0.078***
	(0.014)	(0.023)	(0.029)	(0.015)	(0.021)	(0.026)	(0.016)	(0.022)	(0.027)
DIG×IQ	−0.013	−0.041*	−0.071**	0.018	0.044*	0.069**	0.028*	0.057**	0.084***
	(0.012)	(0.021)	(0.027)	(0.014)	(0.020)	(0.024)	(0.015)	(0.021)	(0.026)
GDPPC	0.041*	0.072**	0.108***	−0.013	−0.021	−0.036	0.008	0.017	0.028

Variables	CO ₂ Q0.25	CO ₂ Q0.50	CO ₂ Q0.75	REN Q0.25	REN Q0.50	REN Q0.75	ELEC Q0.25	ELEC Q0.50	ELEC Q0.75
HC	−0.014	−0.027	−0.043*	0.018	0.036*	0.058**	0.024	0.051**	0.076***
URB	0.019	0.042*	0.068**	−0.008	−0.014	−0.022	0.012	0.031	0.049*
Model Diagnostics									
Diagnostics				CO ₂		REN		ELEC	
Countries				36		36		36	
Observations				468		468		468	
Quantiles estimated				0.25, 0.50, 0.75		0.25, 0.50, 0.75		0.25, 0.50, 0.75	
Pseudo R ² (avg.)				0.43		0.39		0.47	
Model stability				Stable		Stable		Stable	

Notes: Standard errors in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.10.

The MMQR results in Table 9 reveal substantial heterogeneity in the sustainability effects of financial transformation across quantiles. For carbon emissions, the positive effect of financial development increases progressively from lower to higher quantiles, suggesting that financial expansion generates stronger emission-increasing effects among countries with relatively poorer environmental performance. Conversely, the nonlinear component of financial development becomes increasingly negative across higher quantiles, indicating that threshold effects become more pronounced among countries experiencing greater environmental pressure.

Financial inclusion and digitalisation demonstrate stronger sustainability-enhancing effects at higher quantiles, implying that their contribution becomes more substantial among countries facing greater sustainability challenges. For example, the emission-reducing effect of digitalisation increases from statistically insignificant at lower quantiles to strongly significant at upper quantiles, suggesting that digital transformation may be particularly important for countries with relatively higher carbon intensity.

Similarly, interaction effects involving institutional quality strengthen across quantiles, indicating that governance environments become increasingly important as sustainability challenges intensify. The larger coefficients associated with $(FD \times IQ)$ and $(DIG \times IQ)$ at upper quantiles suggest that stronger institutions amplify the sustainability benefits of financial transformation more substantially among countries exhibiting poorer sustainability outcomes.

Overall, the MMQR estimates indicate that financial transformation does not influence sustainability transitions uniformly across SSA economies. Rather, the effects vary according to countries' sustainability conditions, implying that policies aimed at promoting sustainable transitions may require differentiated approaches depending on development levels, institutional environments, and existing sustainability performance.

5.4 Institutional Threshold Effects: Evidence from Dynamic Panel Threshold Estimates

This section examines whether the sustainability effects of financial transformation change beyond specific levels of institutional quality. The Dynamic Panel Threshold Model (DPTM) is employed to identify critical governance thresholds under which financial development shifts from reinforcing environmental pressure to supporting sustainability transitions. This approach is particularly relevant in the SSA context, where substantial institutional heterogeneity may determine whether financial resources are allocated toward carbon-intensive activities or sustainable investments.

The results in Table 10 reveal a statistically significant institutional threshold at approximately $IQ = -0.38$, suggesting that the sustainability effects of financial transformation differ substantially across governance environments. Under weaker institutional conditions ($IQ \leq -0.38$), financial development significantly increases carbon emissions while exerting negative effects on renewable energy adoption and electricity access. Specifically, a 1% increase in financial development increases carbon emissions by approximately 0.271%, indicating that financial expansion in weak institutional settings may reinforce environmentally intensive activities.

Table 10. Dynamic Panel Threshold Estimates: Institutional Quality as Threshold Variable

Variables	Regime 1: (IQ ≤ -0.38)	Regime 2: (IQ > -0.38)	Regime 1: (IQ ≤ -0.38)	Regime 2: (IQ > -0.38)	Regime 1: (IQ ≤ -0.38)	Regime 2: (IQ > -0.38)
	CO ₂	CO ₂	REN	REN	ELEC	ELEC
FD	0.271*** (0.081)	0.092* (0.049)	-0.148** (0.064)	-0.037 (0.041)	-0.121** (0.059)	-0.028 (0.037)
FD²	-0.041 (0.029)	-0.114*** (0.033)	0.051* (0.031)	0.127*** (0.036)	0.044 (0.028)	0.118*** (0.034)
INC	-0.033 (0.022)	-0.069** (0.027)	0.058* (0.029)	0.119*** (0.034)	0.071** (0.031)	0.148*** (0.037)
DIG	-0.049* (0.028)	-0.112*** (0.033)	0.073** (0.032)	0.164*** (0.038)	0.084** (0.036)	0.192*** (0.041)
GDPPC	0.092**	0.047*	-0.031	-0.014	0.018	0.009
HC	-0.027	-0.051*	0.034	0.067**	0.052*	0.089***
URB	0.051*	0.071**	-0.018	-0.026	0.029	0.048*

Threshold Diagnostics

Diagnostics	Value
Estimated threshold ((IQ))	-0.38
Bootstrap F-statistic	26.81***
Threshold significance (p-value)	0.000

Diagnostics	Value
Regime observations (Low IQ)	204
Regime observations (High IQ)	264
Threshold effect	Significant
Model stability	Stable

Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

However, above the institutional threshold ($IQ > -0.38$), the adverse environmental effects of financial development weaken considerably, while nonlinear effects become more pronounced. The larger and significant coefficients on FD^2 suggest that stronger institutions accelerate the transition from environmentally intensive growth toward sustainability-enhancing financial systems. Similarly, financial inclusion and digitalisation exhibit stronger positive effects on renewable energy adoption and electricity access under higher institutional quality, implying that governance environments amplify the sustainability benefits of financial transformation.

These findings indicate that institutions determine when finance becomes sustainable. Financial expansion alone appears insufficient for promoting sustainability transitions; rather, stronger governance structures are necessary to redirect financial resources toward cleaner technologies, renewable energy investment, and inclusive infrastructure development. Consequently, institutional strengthening emerges as a prerequisite for transforming financial systems into effective instruments of sustainable development in Sub-Saharan Africa.

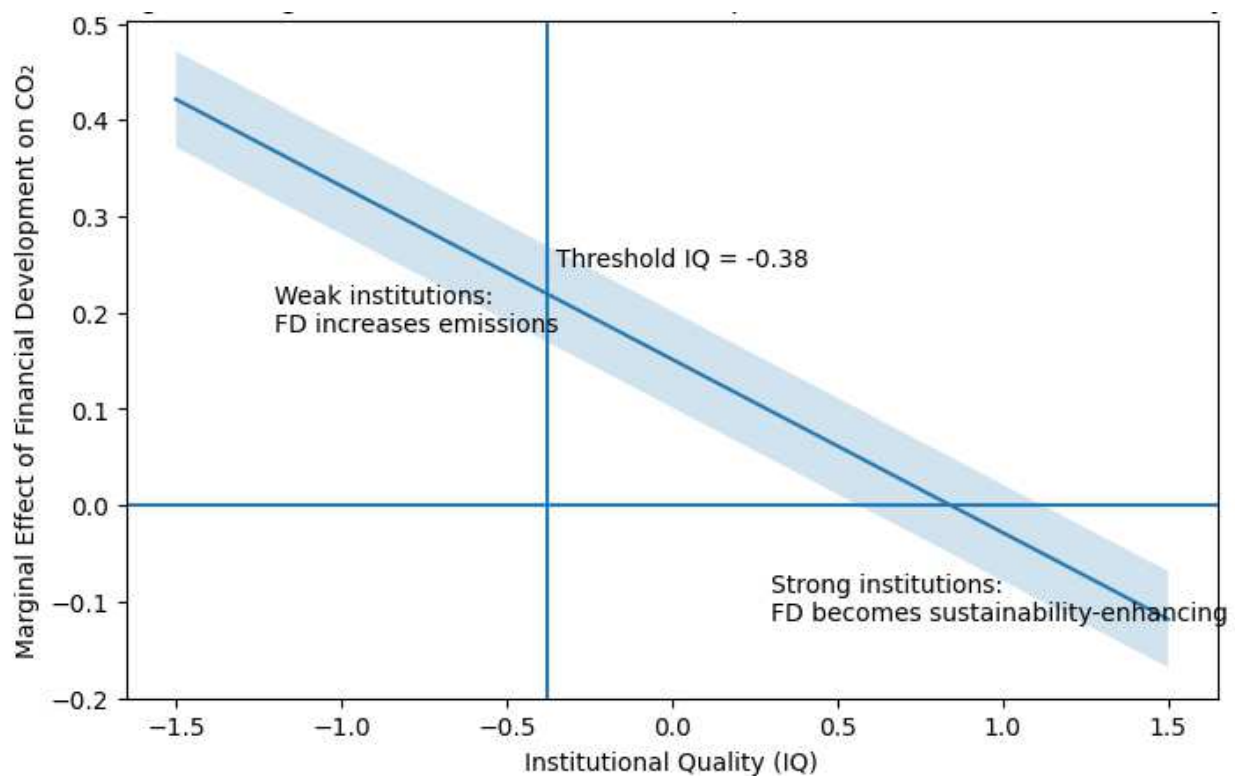


Figure 3. Marginal Effects of Financial Development on Carbon Emissions Across Institutional Quality in Sub-Saharan Africa

Figure 3 illustrates the marginal effect of financial development on carbon emissions conditional on institutional quality. The downward-sloping relationship indicates that the environmental consequences of financial expansion vary systematically across governance environments. Under weaker institutional conditions, financial development exerts a positive effect on carbon emissions, implying reinforcement of environmentally intensive activities. However, as institutional quality

improves, the marginal effect declines and eventually becomes sustainability-enhancing. The vertical reference line denotes the estimated institutional threshold ($IQ = -0.38$), beyond which financial systems increasingly support sustainability transitions rather than environmental pressure. Shaded bands represent confidence intervals around the estimated marginal effects.

Table 11 integrates evidence across estimators and summarises the key mechanisms through which financial transformation influences sustainability outcomes. The findings collectively indicate that sustainability transitions emerge through nonlinear, heterogeneous, and institutionally conditioned pathways rather than through financial expansion alone.

Table 11. Synthesis of Empirical Findings and Implications for Sustainability Transitions in Sub-Saharan Africa

Empirical Dimension	Main Finding	Evidence Source	Interpretation	Sustainability Implication
Financial Development (FD)	Financial expansion initially increases CO ₂ emissions while reducing renewable energy adoption and electricity access	CS-ARDL; DCCE-MG	Financial deepening alone reinforces environmentally intensive activities during early stages	Expanding finance without transformation may worsen sustainability outcomes
Nonlinear Effects (FD ²)	The adverse effects of finance diminish beyond critical thresholds; sustainability gains emerge at higher levels of financial maturity	CS-ARDL; DCCE-MG; MMQR	The finance–sustainability relationship is nonlinear rather than constant	Financial systems become sustainability-enhancing only after structural maturation
Financial Inclusion (INC)	Inclusion reduces emissions and improves renewable energy adoption and electricity access	CS-ARDL; DCCE-MG; MMQR	Broader access to financial services supports cleaner investment and resilience	Inclusive finance functions as a sustainability accelerator
Digitalisation (DIG)	Digitalisation exerts the strongest positive sustainability effects across indicators	CS-ARDL; DCCE-MG; MMQR	Digital systems improve efficiency, reduce frictions, and facilitate sustainable technologies	Digital transformation accelerates sustainability transitions
Institutional Quality (IQ)	Strong institutions amplify the sustainability effects of finance and digitalisation	Interaction models; Threshold estimates	Governance determines whether finance supports sustainability or carbon-intensive growth	Institutional strengthening is a prerequisite for sustainable financial systems

Empirical Dimension	Main Finding	Evidence Source	Interpretation	Sustainability Implication
Heterogeneity (MMQR)	Sustainability effects become stronger among countries with greater environmental pressure	MMQR	Financial transformation affects countries differently depending on sustainability conditions	Uniform sustainability policies may be ineffective across SSA
Threshold Effects	Financial systems become progressively sustainability-enhancing once institutional quality exceeds critical levels	Dynamic Threshold Model	Institutional environments determine when finance shifts from adverse to beneficial effects	Governance reforms lower barriers to sustainability transitions
Robustness Across Estimators	Findings remain consistent under alternative estimators controlling for common shocks and heterogeneity	DCCE-MG; MMQR	Results are stable and not estimator-specific	Evidence supports persistent nonlinear sustainability pathways
Overall Synthesis	Sustainability transitions depend on transformation through inclusion, digitalisation, and institutions rather than financial expansion alone	All estimators	Finance contributes through structural transformation rather than scale effects	Sustainable development requires transforming financial systems rather than simply expanding them

6. Discussion

The findings provide new evidence that financial transformation influences sustainability transitions in Sub-Saharan Africa through nonlinear and institutionally conditioned pathways rather than through financial expansion alone. Across estimators, the results consistently show that financial development initially increases environmental pressure but becomes progressively sustainability-enhancing beyond certain thresholds. Meanwhile, financial inclusion and digitalisation exhibit relatively stable positive effects, while institutional quality determines the extent to which financial systems support sustainability outcomes. These findings collectively suggest that sustainability transitions depend more on how financial systems evolve than on the mere expansion of financial resources.

The positive relationship between financial development and carbon emissions in the early stages of financial expansion suggests that increasing access to credit and financial resources may initially reinforce environmentally intensive production structures. This finding aligns with arguments that

financial deepening in developing economies often supports industrialisation, infrastructure expansion, and resource-intensive activities before sustainability objectives become integrated into investment decisions.

However, the significant nonlinear effects indicate that these relationships change as financial systems mature. Beyond certain thresholds, financial development begins to reduce environmental pressure while supporting renewable energy adoption and electricity access. This pattern implies that mature financial systems may improve resource allocation efficiency, facilitate technological upgrading, and increase investment in sustainable sectors. Consequently, the findings support the proposition that the relationship between finance and sustainability is dynamic rather than linear, with sustainability gains emerging only after sufficient financial maturity has been achieved.

The evidence extends previous finance–environment literature by suggesting that financial development alone cannot be assumed to produce sustainability benefits, particularly within contexts characterised by structural constraints and uneven institutional environments.

The positive effects of financial inclusion and digitalisation indicate that broader access to financial services and digital infrastructure contributes meaningfully to sustainability transitions. Unlike financial depth, which initially reinforces environmental pressure, inclusion and digitalisation exhibit more consistently favourable effects across sustainability indicators.

These findings are particularly relevant for SSA, where mobile money systems have transformed financial access beyond traditional banking infrastructure. Expanded inclusion may improve households' and firms' ability to finance renewable technologies, manage risks, and invest in productive activities. Similarly, digitalisation appears to reduce informational frictions, lower transaction costs, and facilitate diffusion of sustainable technologies.

The stronger sustainability effects associated with digitalisation suggest that technological transformation may accelerate sustainability transitions by overcoming geographic and infrastructural barriers that historically constrain development in the region.

One of the most important findings concerns the role of institutional quality. The interaction and threshold estimates consistently indicate that stronger institutions amplify the sustainability benefits of financial transformation. Under weak governance environments, financial expansion appears more likely to reinforce carbon-intensive activities. Conversely, stronger institutions increase the likelihood that financial resources are channelled toward sustainable investments and cleaner technologies.

These findings imply that institutions function as enabling conditions determining whether financial transformation contributes to sustainability transitions. In practical terms, improving regulatory quality, governance effectiveness, and policy implementation capacity may be necessary for converting financial expansion into sustainable development outcomes.

The threshold evidence further suggests that institutional improvements generate nonlinear benefits, indicating that modest improvements may produce limited effects until governance conditions exceed critical levels.

Collectively, the findings imply that sustainability transitions in SSA require a shift from policies emphasising financial expansion toward strategies promoting financial transformation. Expanding financial systems without strengthening inclusion, digitalisation, and institutional environments may generate limited sustainability benefits and potentially intensify environmental pressure.

Instead, sustainability transitions appear more likely where financial systems become increasingly inclusive, digitally enabled, and institutionally supported. Thus, the results suggest that finance contributes to sustainable development primarily through structural transformation processes that improve accessibility, efficiency, and governance rather than through increases in financial depth alone. Overall, the study advances a financial transformation perspective on sustainability transitions, highlighting the importance of understanding finance as an evolving system whose environmental consequences depend on institutional and developmental contexts.

7. Policy Implications

The findings carry important implications for sustainability transitions in Sub-Saharan Africa, particularly in contexts characterised by financial exclusion, weak institutional environments, persistent energy poverty, and uneven digital transformation. The evidence consistently indicates that financial expansion alone is insufficient to support sustainable development outcomes. Instead, sustainability gains emerge when financial systems become increasingly inclusive, digitally enabled, and institutionally supported. Consequently, policies aimed at accelerating sustainability transitions should prioritise financial transformation rather than financial deepening in isolation.

7.1 Prioritising Financial Transformation over Financial Expansion

The nonlinear effects of financial development suggest that expanding credit and financial resources without complementary reforms may initially intensify environmental pressure. Policymakers should therefore move beyond conventional objectives centred solely on increasing financial depth and instead promote financial systems capable of directing resources toward sustainable sectors. This requires integrating environmental considerations into financial regulation, strengthening green finance mechanisms, and incentivising investments supporting renewable energy and sustainable infrastructure.

7.2 Expanding Financial Inclusion as a Sustainability Instrument

The positive effects of financial inclusion imply that broader access to financial services contributes to renewable energy adoption and improved electricity access. Policies supporting mobile money expansion, digital banking access, and affordable financial services may therefore generate sustainability benefits beyond traditional financial outcomes. In regions characterised by

persistent exclusion, improving access to finance may strengthen resilience, facilitate investment in cleaner technologies, and support inclusive sustainability transitions.

7.3 Accelerating Digital Financial Ecosystems for Sustainable Development

The relatively strong sustainability effects associated with digitalisation indicate that digital transformation may function as an accelerator of sustainability transitions. Investments in digital infrastructure, internet penetration, and mobile financial technologies should therefore be considered integral components of sustainability strategies. Strengthening digital ecosystems may reduce transaction costs, improve information access, and facilitate adoption of sustainable technologies, particularly in underserved areas.

7.4 Strengthening Institutions to Enable Sustainable Financial Systems

The interaction and threshold findings demonstrate that institutional quality determines whether financial transformation supports sustainability outcomes. Consequently, improving regulatory quality, governance effectiveness, and policy implementation capacity should constitute a central component of sustainability strategies. Institutional strengthening is likely to enhance resource allocation efficiency and increase the capacity of financial systems to support environmentally sustainable investments.

7.5 Advancing Integrated Policies for Sustainability Transitions

The findings further suggest that isolated interventions may generate limited sustainability benefits. Policies targeting financial development, inclusion, digitalisation, and institutional improvement should therefore be pursued in a coordinated manner. Integrated approaches are more likely to generate synergies capable of accelerating progress toward SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) while simultaneously supporting inclusive development objectives.

Overall, the evidence indicates that achieving sustainability transitions in Sub-Saharan Africa requires transforming financial systems into mechanisms that promote accessibility, digital efficiency, and institutional effectiveness. Thus, sustainable development depends not only on the expansion of finance but on the conditions under which finance evolves and operates.

8. Conclusion and Limitations

This study examined the role of financial transformation in shaping sustainability transitions in Sub-Saharan Africa, focusing on the nonlinear effects of financial development, financial inclusion, digitalisation, and institutional quality. Using complementary estimators, including CS-ARDL, DCCE-MG, MMQR, and Dynamic Panel Threshold Models, the analysis provides evidence that the sustainability implications of finance are dynamic, heterogeneous, and institutionally conditioned.

The findings reveal that financial development initially increases environmental pressure, reflected in higher carbon emissions and weaker sustainability outcomes. However, nonlinear estimates indicate that these adverse effects diminish beyond certain thresholds of financial maturity, suggesting that finance becomes progressively sustainability-enhancing over time. In contrast, financial inclusion and digitalisation consistently promote sustainability transitions by reducing emissions while improving renewable energy adoption and electricity access. Institutional quality further emerges as a critical enabling factor, with stronger governance environments amplifying the sustainability benefits of financial transformation. Threshold estimates confirm that institutions determine when financial systems transition from reinforcing carbon-intensive growth to supporting sustainable development.

These findings contribute to the literature by advancing a financial transformation perspective, arguing that sustainability outcomes depend not on financial expansion alone but on how financial systems evolve through inclusion, digitalisation, and institutional strengthening. The results imply that policies aimed at accelerating sustainability transitions in SSA should prioritise inclusive financial systems, digital financial ecosystems, and stronger governance frameworks rather than focusing solely on financial deepening.

Despite these contributions, several limitations remain. First, the use of aggregate country-level indicators may mask within-country heterogeneity. Second, although multiple estimators address endogeneity concerns, causal inference remains limited by observational data. Third, digitalisation measures may not fully capture differences in the intensity and quality of digital financial usage. Future research could employ micro-level data, alternative identification strategies, and additional institutional dimensions to deepen understanding of finance–sustainability relationships. Overall, the evidence suggests that sustainability transitions in Sub-Saharan Africa depend less on expanding finance and more on transforming finance into an inclusive, digital, and institutionally supported system capable of advancing long-term sustainable development.

Data Availability

Data available upon request

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