

The Mediating role of Digital Financial Inclusion on the relationship between Green Finance and Carbon Emission in Africa

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Abstract

Climate change has become one of the most pressing global challenges, with developing regions such as Africa facing disproportionate environmental risks despite contributing minimally to global emissions. At the same time, the continent continues to grapple with significant development constraints, including limited access to energy and financial services. In this context, green finance and digital financial inclusion have emerged as critical mechanisms for promoting sustainable development; however, their combined effect on environmental outcomes remains insufficiently explored. This study examines the relationship between green finance, digital financial inclusion, and carbon emissions across 48 African countries, with particular emphasis on the mediating role of digital financial inclusion. Using Partial Least Squares Structural Equation Modeling, the study analyzes both direct and indirect relationships among the constructs. The findings reveal that green finance has a significant negative effect on carbon emissions, confirming its role in promoting environmental sustainability. In addition, green finance significantly enhances digital financial inclusion, highlighting the strong link between financial sustainability and technological innovation. Furthermore, digital financial inclusion is found to significantly reduce carbon emissions. Importantly, the results confirm that digital financial inclusion partially mediates the relationship between green finance and carbon emissions, indicating that the environmental benefits of green finance are amplified when supported by digital financial systems. The study contributes to the literature by integrating Financial Intermediation Theory and Diffusion of Innovation Theory and underscores the need for integrated policy approaches to achieve sustainable environmental outcomes in Africa.

1. Introduction

Climate change has emerged as one of the most pressing global challenges of the twenty-first century, with significant implications for economic development, environmental sustainability, and human well-being. Recent data indicate that global greenhouse gas emissions continue to rise despite international mitigation efforts. Atmospheric carbon dioxide (CO₂) concentrations reached approximately 423 ppm in 2024, representing the highest level in recorded history, while methane (CH₄) and nitrous oxide (N₂O) levels have also continued to increase (Alrifadi et al., 2026; Cifuentes-Faura et al., 2026). Global CO₂ emissions reached record highs in 2023 and 2024, further narrowing the carbon budget required to limit global warming to 1.5°C (Criste et al., 2026; Demirkale et al., 2025). These trends have been accompanied by increasing climate-related disasters, including extreme temperatures, floods, and droughts, with global economic losses estimated at over US\$200 billion annually (Gulati et al., 2026). These developments underscore the urgent need for sustainable and innovative solutions to reduce emissions while supporting economic growth.

Among the various policy responses to climate change, green finance has gained increasing prominence as a key mechanism for promoting low-carbon development. Green finance refers to financial investments directed toward environmentally sustainable projects, such as renewable energy, energy efficiency, and climate-resilient infrastructure (Gutu et al., 2025). By mobilizing capital toward

environmentally friendly activities, green finance plays a crucial role in reducing carbon emissions and supporting sustainable development. However, while the importance of green finance is widely acknowledged, its effectiveness depends largely on the mechanisms through which financial resources are accessed and utilized, particularly in developing economies.

In parallel, the rapid expansion of digital financial inclusion has transformed financial systems globally. Digital financial inclusion refers to the use of digital technologies, including mobile money, fintech platforms, and digital payments, to provide accessible and affordable financial services (Hussain et al., 2026). Globally, mobile money transactions exceeded US\$1.4 trillion in 2023, with Sub-Saharan Africa accounting for the largest share of users and transaction volumes (Kang et al., 2026). The region alone processes over 60 percent of global mobile money transactions, highlighting the critical role of digital finance in expanding financial access (Kashif et al., 2026). Digital financial inclusion not only improves financial access but also has the potential to support environmental sustainability by enabling access to clean energy financing, improving efficiency, and facilitating sustainable consumption patterns (Li & Yang, 2026).

The connection between green finance and digital financial inclusion is increasingly recognized as important for achieving environmental sustainability. While green finance provides the capital necessary for environmental investments, digital financial inclusion serves as a delivery mechanism that enhances access to financial resources. This suggests that digital financial inclusion may strengthen the impact of green finance on carbon emissions by improving financial accessibility, reducing transaction costs, and supporting the adoption of sustainable technologies. However, empirical evidence on this interaction remains limited.

The African context provides a unique and relevant setting for examining these relationships. Although Africa contributes less than 4 percent of global greenhouse gas emissions, it is among the most vulnerable regions to climate change (Li et al., 2026; Liu et al., 2026). Climate-related challenges such as droughts, floods, and food insecurity continue to affect economic and social development across the continent (Maket, 2026). At the same time, Africa has experienced rapid growth in digital financial services, particularly mobile money, which has significantly improved financial inclusion in countries such as Kenya, Ghana, and Nigeria (Mnatsakanyan & Karapetyan, 2026). In addition, there has been increasing interest in green finance initiatives across the continent, supported by international organizations and development partners (Mori, 2026). This combination of high climate vulnerability, expanding digital financial systems, and growing green finance initiatives makes Africa an ideal context for this study.

Despite these developments, several important research gaps remain. First, existing studies often examine green finance and environmental sustainability without considering the role of digital financial inclusion as a facilitating mechanism. Second, studies on financial inclusion and environmental outcomes tend to focus on traditional financial systems, with limited attention to digital financial inclusion, which is more relevant in developing economies. Third, empirical evidence from African

countries remains limited, despite the region's unique characteristics. Finally, the mediating role of digital financial inclusion in the relationship between green finance and carbon emissions has received little attention in the literature.

These gaps provide the motivation for this study, which seeks to examine the relationships among green finance, digital financial inclusion, and carbon emissions in Africa. Specifically, the study addresses the following research questions: (i) Does green finance significantly influence carbon emissions in African countries? (ii) What is the effect of green finance on digital financial inclusion? (iii) Does digital financial inclusion significantly influence carbon emissions? and (iv) Does digital financial inclusion mediate the relationship between green finance and carbon emissions? To address these questions, this study employs Partial Least Squares Structural Equation Modeling (PLS-SEM) using data from 48 African countries. This approach allows for the simultaneous estimation of direct and indirect relationships among the study variables.

This study makes several important and original contributions to the literature on sustainable finance, digital transformation, and environmental economics. First, it advances existing knowledge by developing an integrated analytical framework that simultaneously examines green finance, digital financial inclusion, and carbon emissions, rather than treating these constructs in isolation as commonly done in prior studies. While previous research has largely focused on the direct impact of green finance on environmental outcomes or the role of financial inclusion in economic development, this study bridges these strands by explicitly modeling their interaction within a unified empirical framework. Second, the study introduces digital financial inclusion as a mediating mechanism, which represents a key conceptual and empirical advancement. By doing so, it moves beyond simple direct-effect models and provides deeper insights into the transmission channels through which green finance influences environmental sustainability. This mediation perspective is largely absent in existing literature, particularly in the context of developing economies, thereby addressing a critical gap and offering a more nuanced understanding of how financial resources translate into environmental outcomes. Third, the study contributes to theory by integrating Financial Intermediation Theory with Diffusion of Innovation Theory, thereby offering a more comprehensive explanation of the joint role of financial systems and digital technologies in driving environmental sustainability. This dual-theoretical approach extends the conceptual boundaries of sustainable finance research by demonstrating that financial capital alone is insufficient without efficient technological delivery mechanisms. Fourth, from a methodological standpoint, the study enhances rigor by employing Partial Least Squares Structural Equation Modeling (PLS-SEM) alongside advanced validation techniques, including mediation analysis, robustness checks, multi-group analysis, predictive relevance assessment, and bias diagnostics. This comprehensive methodological approach strengthens the reliability, validity, and generalizability of the findings. Fifth, the study provides valuable empirical evidence from 48 African countries, a region that remains underrepresented in the sustainability and finance literature despite its high climate vulnerability and rapid digital financial expansion. By focusing on Africa, the study offers context-specific insights and improves the external validity of findings for developing economies.

Finally, the key novelty of this study lies in demonstrating that the environmental impact of green finance is significantly amplified through digital financial inclusion, thereby highlighting the importance of synergy between financial sustainability and digital innovation. This insight shifts the policy narrative from isolated interventions toward integrated strategies, offering practical implications for governments, financial institutions, and development agencies seeking to achieve sustainable environmental outcomes.

2. Theoretical framework and research hypothesis

2.1 Theoretical framework

2.1.1 Financial Intermediation Theory

The financial intermediation theory was first developed by Peery (1960) and later extended by (Diamond & Dybvig, 1986). The theory accounts for the importance of financial intermediaries including financial institutions, investment funds, and banks in helping to allocate financial resources efficiently from surplus-segments of the economy to deficit-segments of the economy. The theory holds that the financial intermediaries come about because there are often information problems, frictions over transactions, constraints on liquidity, and problems of risk that make it difficult to transact directly between savers and borrowers. Financial intermediaries fill this gap by bringing together savers and redirecting their savings to productive investments that improve economic efficiency and sustainable development (Alrifadi et al., 2026). There are some fundamental assumptions underpinning the theory. Financial intermediaries lower transaction costs due to the economies of scale to which they benefit in gathering and monitoring information, and in enforcing contracts. Second, they help address information asymmetries by efficiently screening and monitoring borrowers, thus lessening adverse selection and moral hazard issues. Third, intermediaries undertake risk diversification by aggregating funds of a number of investors and spreading them over various investment vehicles. Fourth, they are involved in liquidity and maturity transformation, taking in short-term deposits and investing them in long-term projects, which yield greater rewards but take longer to provide returns (Maket, 2026; Mnatsakanyan & Karapetyan, 2026). The financial intermediaries function in ways that allow financial resources to be more efficiently allocated and that increase economic and social welfare. Financial Intermediation Theory has found a broad range of uses in research on sustainable finance and environmental investments. From the lens of the theory, green finance can be seen as a means to promote environmental sustainability by directing financial resources towards environmentally friendly projects. Green finance refers to financial tools and measures that finance renewable energy, energy efficiency, sustainable agriculture and sustainable infrastructure, including green bonds, green loans, sustainable investment schemes, and climate funds (Liu et al., 2026). A financial intermediary helps mobilise and allocate funds to investments that provide environmental benefits and lower carbon emissions in this context. Green finance helps alleviate financing difficulties, and solve information asymmetries in environmental project, thereby facilitating the introduction of green production processes and the

application of low-carbon technologies. The theory is especially pertinent to the current study, in which digital financial inclusion will improve the effectiveness of financial intermediation. Digital payment, mobile money services, crowdfunding platforms, and fintech applications are some of the technological advancements that bring financial services to people who were previously excluded from the financial system but also provide lower transaction costs and enhance financial access (Li et al., 2026). Through these digital platforms, green financial products can be accessed by households, farmers and small enterprises who can be otherwise excluded from the traditional financial system. Therefore, in terms of carbon emission, the green finance function can not only be achieved by direct investment in green projects, but also be achieved through the promotion of digital financial inclusion, which enhances the accessibility, efficiency and outreach of green financial products and services. Hence, from the perspective of carbon emission, the green finance function can be realized not only by direct investment in green projects but also by digital financial inclusion, which promotes the accessibility, efficiency and reach of green financial products and services.

2.1.2 Diffusion of Innovation Theory

Rogers and Cartano (1962) introduced DIT for understanding the process of change over time of innovations, technologies and new ideas in a social system. The theory has since gained global popularity as one of the most widely used models to explain technology adoption and behavioural change in a number of disciplines such as economics, information systems, finance and environmental studies. Li and Yang (2026) hypothesized that adoption of innovations is not an all-or-nothing process, but takes place gradually, responding to the perceived characteristics of the innovation and the social context. The theory highlights five attributes that affect adoption success and rate. They are relative advantage, compatibility, complexity, trialability and observability. Relative advantage is how good an innovation is in comparison to other available alternatives. Compatibility is the extent to which the innovation is compatible with values, experiences, and needs. Complexity is the perceived difficulty of understanding and using an innovation. The opportunities to try out an innovation before committing to its use is referred to as trialability, and the extent to which the results of the innovation are observable to others is referred to as observability (Kang et al., 2026; Kashif et al., 2026). Innovations with greater relative advantage, compatibility, trialability, and observability, and less complexity spread more quickly in society. An additional key area of theory is emphasis on communication channels, social systems and time. Hussain et al. (2026) suggested that there are five stages in the diffusion process: Knowledge, Persuasion, Decision, Implementation, and Confirmation. Individuals are also classified based on their adoption behavior, ranging from innovators, early adopters, early majority, late majority to laggards. The relationship between these groups helps to spread innovations and the rate of acceptance of new technologies. The theory of Diffusion of Innovation (DoI) has been widely applied to understand the swift digital financial technology (DFT) adoption in the developing world. Other innovations in Africa such as mobile money, digital wallets, online banking, fintech platforms and electronic payment systems have boosted digital financial inclusion, significantly. In this regard, these technologies have revolutionized the provisioning of financial services by removing geographical constraints, transaction costs, and making financial services more accessible to underserved population segments (Gutu et al., 2025). Countries

like Ghana, Kenya and Nigeria are examples of the countries whose mobile money services are widely adopted, hence showing the diffusion process described by (Demirkale et al., 2025). Digital financial services are gaining momentum in terms of their perceived convenience, affordability, access and efficiency, and have thus contributed to their adoption by both households and businesses. The theory is also highly relevant to this study as it helps to understand how digital financial inclusion can contribute to the effectiveness of green finance in reducing carbon emissions. Digital financial technologies are increasingly spreading across African economies and are providing efficient channels for access to green financial products to a wider population (Criste et al., 2026). Digital platforms, for instance, can facilitate financing for solar energy, energy efficient appliances, clean cooking technologies and other investments for households and small businesses that are good for the environment. The usage of digital finance services thus broadens access to green finance, and boosts the ability of people and businesses to engage in environmentally sustainable activities. Moreover, according to the Diffusion of Innovation Theory, the environmental benefits of green finance will likely grow with a wider uptake of digital financial inclusion. With an increasing number of people making more use of digital financial products, the scope and impact of green financial products grows, which enables more people to join sustainable investment initiatives and helps to move closer to the goal of reducing carbon emissions. Thus, digital financial inclusion acts as a mediating variable between green finance and carbon emissions, which is supported by the theory. The theory supports digital financial inclusion as a mediator in the relationship between green finance and carbon emissions. By spreading digital financial technologies, green finance can be more inclusive, more accessible and more effective in fostering environmental results and sustainable development and climate change mitigation in Africa.

2.2 Hypothesis Development

2.2.1 Green Finance and Carbon Emissions Nexus

The relationship between green finance and carbon emissions is grounded in Financial Intermediation Theory, which explains the role of financial systems in allocating capital toward productive and sustainable investments. According to this theory, financial intermediaries facilitate the efficient distribution of financial resources by reducing transaction costs, managing risks, and directing capital toward sectors that generate long-term economic and social benefits (Alrifadi et al., 2026; Cifuentes-Faura et al., 2026). In the context of environmental sustainability, green finance represents a mechanism through which financial institutions channel investments toward environmentally friendly projects such as renewable energy, energy efficiency improvements, sustainable agriculture, and low-carbon infrastructure (Zhu et al., 2023). Green finance contributes to reducing carbon emissions by promoting investments that replace carbon-intensive technologies with cleaner alternatives. For example, green bonds, green loans, and climate funds are increasingly used to finance renewable energy projects such as solar, wind, and hydroelectric power, which reduce dependence on fossil fuels and lower greenhouse gas emissions. In addition, green finance supports energy efficiency improvements in industries, transportation systems, and buildings, which reduce energy consumption and emissions intensity. By mobilizing financial resources for environmentally sustainable projects, green finance plays a critical role

in supporting the transition toward low-carbon economic development. Empirical studies provide growing evidence of the environmental benefits of green finance. For instance, (Zaman et al., 2026; Zhang et al., 2026) found that environmental taxes and green public expenditure significantly reduce carbon emissions in African countries by promoting energy efficiency and cleaner production practices. Similarly, Xu and Wang (2025) reported that green investment and structural innovation significantly reduce carbon emissions across African and Asian economies. Study by Xiao et al. (2024) also shows that green bonds have contributed to financing renewable energy and climate-resilient infrastructure projects, which play a key role in reducing greenhouse gas emissions. Furthermore, Wu et al. (2026) argue that green finance mechanisms can help developing economies achieve sustainable development by encouraging environmentally responsible investment and supporting the transition toward cleaner energy systems. In the African context, where energy demand is increasing rapidly, green finance provides a critical pathway for meeting development needs while minimizing environmental damage.

Based on the theoretical foundations of Financial Intermediation Theory and the growing empirical evidence on the environmental benefits of sustainable finance, green finance is expected to reduce carbon emissions by directing capital toward low-carbon investments and environmentally sustainable economic activities.

H₁: Green finance has a significant negative effect on carbon emissions in Africa.

2.2.2 Green Finance and Digital Financial Inclusion Nexus

The relationship between green finance and digital financial inclusion can be explained through the lens of Financial Intermediation Theory and the evolving role of financial innovation in promoting sustainable development. Financial Intermediation Theory suggests that financial systems play a critical role in allocating capital efficiently by reducing transaction costs, addressing information asymmetries, and facilitating access to financial services (Teixeira, 2026; Tsybuliak et al., 2025). In the context of green finance, financial institutions increasingly rely on digital technologies and financial innovations to improve the accessibility and efficiency of environmentally focused financial products. Green finance initiatives often require innovative financial delivery mechanisms to reach households, small businesses, and rural populations that are traditionally excluded from formal financial systems. Digital financial platforms such as mobile money, digital lending, and fintech applications provide cost-effective channels through which green financial products can be distributed. For example, mobile-based financing models allow households to access loans for solar home systems, clean cooking technologies, and other environmentally friendly solutions through small and frequent digital payments (Surwanti et al., 2026; Tang et al., 2026). As green finance expands, financial institutions and governments increasingly integrate digital technologies into financial systems, thereby strengthening digital financial inclusion. Furthermore, investments in green finance often promote financial sector innovation and infrastructure development, including digital payment systems, fintech platforms, and data-driven financial services. These developments improve financial accessibility by lowering transaction costs, expanding service reach to underserved populations, and enhancing financial participation. Consequently, the expansion of green finance can contribute to the growth and adoption of digital financial services, particularly in

developing regions such as Africa where mobile financial technologies play a central role in financial inclusion (Bayong, 2026; Singh et al., 2026). Empirical studies also suggest that sustainable finance initiatives and technological innovations are increasingly interconnected. The integration of fintech solutions into green financing mechanisms enables broader access to financial services while supporting sustainable investment activities (Rani et al., 2025; Saeed & Bayong, 2026). Therefore, the development of green finance is expected to stimulate digital financial inclusion by encouraging the adoption of digital financial platforms and expanding access to environmentally targeted financial services.

Based on this theoretical and empirical reasoning, green finance is expected to positively influence digital financial inclusion.

H₂: Green finance has a significant positive effect on digital financial inclusion in Africa.

2.2.3 Digital Financial Inclusion and Carbon Emissions Nexus

The relationship between digital financial inclusion and carbon emissions can be explained through Diffusion of Innovation Theory, which describes how new technologies spread across populations and influence economic and social behavior (Mori, 2026; Ogunmola, 2026). Digital financial inclusion refers to the use of digital technologies such as mobile money, online banking, digital payments, and fintech platforms to provide financial services to underserved populations (Bayong, Yuorkuu, et al., 2026). As these digital financial technologies diffuse across economies, they create new opportunities for financial access and economic participation while also influencing environmental outcomes. Digital financial inclusion can reduce carbon emissions through several mechanisms. First, digital financial services reduce the need for physical financial transactions, transportation, and paper-based financial activities, thereby lowering energy consumption and emissions associated with traditional banking operations. Second, digital financial inclusion enables households and businesses to access financing for environmentally friendly technologies such as solar energy systems, energy-efficient appliances, and clean cooking technologies. For example, mobile money platforms have enabled pay-as-you-go solar financing models that allow households to adopt renewable energy technologies through small and flexible digital payments (Saeed et al., 2025; Wiredu et al., 2025). Empirical evidence increasingly supports the environmental benefits of digital financial inclusion. KaoDui, Saeed, et al. (2026) found that digital financial inclusion contributes to environmental sustainability by facilitating green technology adoption and improving resource efficiency. Similarly, KaoDui, Kongkuah, et al. (2026) show that digital financial technologies, including mobile financial services and internet usage, significantly improve carbon efficiency in African economies. Dawuni et al. (2026) also report that increased access to digital financial infrastructure such as internet services and financial technologies contributes to lower carbon emissions and higher renewable energy consumption. Furthermore, digital financial inclusion enhances environmental monitoring and verification mechanisms by generating digital transaction data that can support carbon credit programs and climate finance initiatives. Digital platforms can facilitate the

distribution of climate finance and promote sustainable consumption patterns by enabling easier access to environmentally friendly financial products. In the African context, where digital financial technologies such as mobile money have expanded rapidly, digital financial inclusion has the potential to play a significant role in promoting environmentally sustainable economic activities. By expanding financial access, reducing transaction costs, and facilitating investment in clean technologies, digital financial inclusion can contribute to reducing carbon emissions.

Based on the theoretical insights from Diffusion of Innovation Theory and the growing empirical evidence on the environmental impacts of digital financial technologies, digital financial inclusion is expected to reduce carbon emissions.

H₃: Digital financial inclusion has a significant negative effect on carbon emissions in Africa.

2.2.4 The Mediating Role of Digital Financial Inclusion in the Green Finance–Carbon Emissions Relationship

The mediating role of digital financial inclusion in the relationship between green finance and carbon emissions can be understood through the integration of Financial Intermediation Theory and Diffusion of Innovation Theory. Financial Intermediation Theory suggests that financial systems facilitate the allocation of capital toward productive and environmentally sustainable investments by reducing transaction costs and overcoming information asymmetries (Alrifadi et al., 2026; Cifuentes-Faura et al., 2026). Green finance plays an important role in directing financial resources toward renewable energy projects, energy-efficient technologies, and environmentally sustainable infrastructure, which contribute to the reduction of carbon emissions (Criste et al., 2026). However, the effectiveness of green finance largely depends on the mechanisms through which financial resources reach end-users. In many African countries, traditional banking infrastructure remains limited, particularly in rural areas, which restricts access to green financial products. Digital financial inclusion can overcome these barriers by providing digital platforms such as mobile money, digital payments, and fintech-based lending services that expand financial access and reduce transaction costs (Demirkale et al., 2025). Empirical evidence suggests that digital financial inclusion plays an important role in supporting environmental sustainability and facilitating access to clean technologies. For example, Gulati et al. (2026) found that digital financial inclusion contributes to environmental improvement by enabling investments in green technologies and reducing carbon emissions. Similarly, Gutu et al. (2025) show that mobile financial technologies improve carbon efficiency in African economies by facilitating financial access to environmentally sustainable investments. In addition, studies by (Bayong, Alagidede, et al., 2026; Dawuni et al., 2026) demonstrate that mobile money platforms enable pay-as-you-go financing models that allow households to adopt solar home systems and other clean energy technologies. Furthermore, digital financial inclusion enhances the effectiveness of green finance by providing digital channels that allow green financial products to reach households and small businesses more efficiently. Through mobile-based financial services, financial institutions can deliver green loans, renewable energy financing, and environmental investment products to populations that are traditionally excluded from formal financial

systems. As digital financial services continue to diffuse across African economies, they strengthen the capacity of green finance to support low-carbon investments and environmentally sustainable practices. Therefore, digital financial inclusion serves as a critical transmission mechanism through which green finance can influence environmental outcomes. By expanding financial access, reducing transaction costs, and facilitating the adoption of clean technologies, digital financial inclusion strengthens the environmental impact of green finance and contributes to reducing carbon emissions.

Based on this theoretical and empirical reasoning, digital financial inclusion is expected to mediate the relationship between green finance and carbon emissions.

H₄: Digital financial inclusion significantly mediates the relationship between green finance and carbon emissions in Africa.

3. Methodology

3.1 Research design, sample and data source

This study adopts a quantitative research approach using a cross-sectional design based on secondary data obtained from multiple reputable international databases. The quantitative approach is appropriate because it enables the empirical testing of hypotheses derived from Financial Intermediation Theory and Diffusion of Innovation Theory, while examining the relationships among green finance, digital financial inclusion, and carbon emissions. The cross-sectional design utilizes data for the year 2024, providing a contemporary assessment of these relationships across African countries. The choice of 2024 is justified by the increasing prominence of climate finance initiatives, the rapid expansion of digital financial services, and the availability of recent and comparable data across countries. Although cross-sectional studies do not establish causality, they are suitable for identifying associations among variables and testing mediation effects within a structural equation modeling framework. The target population comprises all 54 member states of the African Union. A purposive sampling technique was employed, whereby countries with complete and reliable data for all study variables were selected. This resulted in a final sample of 48 African countries, representing approximately 89% of the continent. The sample covers all five African regions, thereby ensuring broad geographical representation and capturing variations in economic development, financial inclusion, environmental performance, and green finance practices. Data for the study were obtained from credible secondary sources, including international databases and institutional reports that provide standardized country-level indicators. The use of multiple data sources enhances the reliability, validity, and comparability of the data across countries. Regarding sample adequacy, (Appiah et al., 2026; Hussain et al., 2026) note that PLS-SEM can produce reliable estimates with relatively small samples, particularly when the model exhibits strong measurement properties and substantial effect sizes. Although the sample size of 48 countries is below the conventional “10-times rule” threshold, PLS-SEM remains appropriate due to its suitability for exploratory and predictive research with limited samples. Table 1 presents the study variables, measurement indicators, and corresponding data sources.

Table 1
Constructs and Indicators

Construct	Measurement Indicators	Acronym	Source	Year
Green Finance	Green bond issuance (USD millions)	GF1	World Bank (WDI)	2024
	Renewable energy investment (USD millions)	GF2	World Bank (WDI)	2024
	Environmental tax revenue (% of GDP)	GF3	World Bank (WDI)	2024
	Public environmental expenditure (% of GDP)	GF4	World Bank (WDI)	2024
Digital Financial Inclusion	Mobile money account penetration (% of adults)	DFI1	World Bank (WDI)	2024
	Mobile money transaction value (% of GDP)	DFI2	World Bank (WDI)	2024
	Mobile money agent density (per 100,000 adults)	DFI3	World Bank (WDI)	2024
	Digital payments usage (% of adults)	DFI4	World Bank (WDI)	2024
	Mobile broadband subscriptions (per 100 adults)	DFI5	World Bank (WDI)	2024
Carbon Emissions (CE)	CO ₂ emissions per capita (metric tons)	CE1	World Bank (WDI)	2024
	CO ₂ emissions intensity (kg per USD of GDP)	CE2	World Bank (WDI)	2024
	Total CO ₂ emissions (kilotons, kt)	CE3	World Bank (WDI)	2024
	CO ₂ emissions from fuel combustion (%)	CE4	World Bank (WDI)	2024

Due to the extensive geographical coverage of 48 African countries and limitations in time and resources, primary data collection was not feasible. Consequently, this study relies on secondary data obtained from reputable international databases, ensuring data reliability, consistency, and comparability across countries. The conceptual framework comprises three core latent constructs: green finance, digital financial inclusion, and carbon emissions, alongside six control variables. Green finance is measured using four indicators reflecting market-based and public-sector financing activities. Digital financial inclusion is assessed through five indicators covering access, usage, and infrastructure dimensions, while carbon emissions are measured using emissions intensity and per capita emissions indicators. Control variables include GDP per capita, population size, urbanization rate, industrialization, renewable energy share, and institutional quality.

3.4 Analysis Techniques

The analysis of PLS-SEM data follows a two-stage approach: assessment of the measurement model, followed by evaluation of the structural model (Appiah et al., 2026; Bayong et al., 2024). The measurement model assessment evaluates the relationships between latent constructs and their observed indicators, while the structural model assessment examines the hypothesized relationships among constructs.

Measurement Model Assessment

All constructs in this study are specified as reflective constructs, meaning that the indicators are viewed as manifestations or effects of the underlying latent construct. For reflective constructs, the following criteria are used to assess measurement model validity and reliability:

Indicator Reliability: Assessed by examining the outer loadings of each indicator on its respective construct. Following Kang et al. (2026), indicator loadings should be 0.708 or higher, indicating that the construct explains more than 50% of the indicator's variance. Indicators with loadings between 0.40 and 0.70 may be considered for removal if their deletion improves composite reliability or average variance extracted.

Internal Consistency Reliability: Assessed using composite reliability (CR) and Cronbach's alpha. Composite reliability values between 0.70 and 0.95 are considered satisfactory (Zhou et al., 2026). Cronbach's alpha provides a more conservative estimate, with values above 0.70 indicating acceptable reliability.

Convergent Validity: Assessed using the Average Variance Extracted (AVE), which measures the amount of variance captured by a construct relative to the variance due to measurement error. An AVE value of 0.50 or higher indicates that the construct explains at least 50% of the variance of its indicators, demonstrating adequate convergent validity (Kashif et al., 2026; Zhou et al., 2024).

Discriminant Validity: Assessed using three criteria. First, the Fornell-Larcker criterion requires that the square root of each construct's AVE be greater than its highest correlation with any other construct. Second, cross-loadings are examined to ensure that each indicator loads highest on its intended construct. Third, the Heterotrait-Monotrait (HTMT) ratio of correlations is assessed, with values below 0.90 indicating acceptable discriminant validity (Li & Yang, 2026).

Structural Model Assessment

Following confirmation of measurement model validity and reliability, the structural model is evaluated using five key procedures recommended by (Li et al., 2026; Liu et al., 2026). **Assessment for Collinearity Issues:** The variance inflation factor (VIF) is examined to assess potential collinearity among predictor constructs. VIF values below 5 (more conservatively, below 3) indicate that collinearity is not a concern.

Assessment of Path Coefficient Significance and Relevance: The significance of path coefficients is assessed using bootstrapping with 5,000 resamples to generate t-statistics and confidence intervals. Path coefficients are evaluated in terms of their sign (positive or negative), magnitude, and statistical significance ($p < 0.05$). The relevance of relationships is assessed based on the size of path coefficients.

Assessment of Effect Size (f^2): The f^2 effect size measures the change in R^2 when a specified exogenous construct is omitted from the model. Following Cifuentes-Faura et al. (2026), f^2 values of 0.02, 0.15, and 0.35 represent small, medium, and large effects, respectively.

Assessment of Predictive Relevance (Q^2): The Stone-Geisser Q^2 value is obtained through blindfolding to assess the model's predictive relevance. Q^2 values greater than zero indicate that the model has predictive relevance for a given endogenous construct.

Assessment of Coefficient of Determination (R^2): The R^2 value measures the proportion of variance in endogenous constructs explained by the model. Following Maket (2026), R^2 values of 0.25, 0.50, and 0.75 are considered weak, moderate, and substantial, respectively.

3.6.2.3 Mediation Analysis

To test the mediating role of digital financial inclusion (H_3), the study employs the approach recommended by Babiker et al. (2025) and implemented in PLS-SEM. The significance of the indirect effect (green finance $\rightarrow$ digital financial inclusion $\rightarrow$ carbon emissions) is assessed using bootstrapping with 5,000 resamples to generate confidence intervals. Mediation is supported if the confidence interval for the indirect effect does not include zero. The variance accounted for (VAF) is calculated to determine the size of the indirect effect relative to the total effect, indicating the extent of mediation.

4. Results and Discussion

4.1 Measurement Model Assessment

The measurement model assessment focuses on evaluating the reliability and validity of the constructs employed in the study, namely green finance (GF), digital financial inclusion (DFI), and carbon emissions (CE). Ensuring the adequacy of the measurement model is a critical step in PLS-SEM, as it confirms that the observed indicators accurately represent the underlying latent constructs.

This assessment involves four key components: indicator reliability, internal consistency reliability, convergent validity, and discriminant validity. Indicator reliability is examined through outer loadings to determine the strength of the relationship between each indicator and its respective construct. Internal consistency reliability is assessed using Cronbach's alpha and composite reliability to ensure consistency among indicators. Convergent validity is evaluated using the Average Variance Extracted (AVE), which measures the extent to which a construct explains the variance of its indicators. Finally,

discriminant validity is assessed to confirm that the constructs are distinct from one another and capture different concepts within the model.

4.2.1 Constructs Reliability and Validity

Per Table 2, the reliability and convergent validity of the constructs were assessed using Cronbach's alpha, composite reliability (ρ_a and ρ_c), and average variance extracted (AVE), following the guidelines recommended by (Alazaiza & Al-Zghoul, 2025). These measures are fundamental in Partial Least Squares Structural Equation Modeling (PLS-SEM) as they ensure that the constructs are internally consistent and that the observed indicators adequately capture the underlying latent variables.

Cronbach's alpha was first examined to assess the internal consistency of the constructs. The results indicate that carbon emissions (0.986), digital financial inclusion (0.967), and green finance (0.974) all exceed the minimum threshold of 0.70, suggesting a high degree of reliability among the indicators (Alhassan & Maiga, 2025). These values imply that the items used to measure each construct are highly correlated and consistently reflect the same underlying concept.

In addition to Cronbach's alpha, composite reliability (ρ_c) was used as a more robust measure of internal consistency, as it does not assume equal indicator loadings. The composite reliability values for carbon emissions (0.990), digital financial inclusion (0.974), and green finance (0.981) are all well above the recommended threshold of 0.70. This further confirms that the constructs exhibit strong internal consistency and that the measurement model is reliable. Similarly, the ρ_a values are also above the acceptable level, reinforcing the stability and reliability of the constructs.

Convergent validity was assessed using the Average Variance Extracted (AVE), which measures the extent to which a construct explains the variance of its indicators. According to (Chandra, 2025; Cho & Ackom, 2025), an AVE value of at least 0.50 is required to establish adequate convergent validity. The results show that the AVE values for carbon emissions (0.960), digital financial inclusion (0.883), and green finance (0.929) significantly exceed this threshold. This indicates that a large proportion of the variance in the indicators is explained by their respective constructs, confirming strong convergent validity.

The results per Table 2 demonstrate that the measurement model exhibits excellent internal consistency reliability and convergent validity. The high values across all reliability and validity measures suggest that the constructs are well-defined and appropriately measured, thereby providing a solid foundation for subsequent structural model analysis.

Table 2
Constructs reliability and validity

Constructs	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Carbon Emission	0.986	0.986	0.990	0.960
Digital Financial Inclusion	0.967	0.967	0.974	0.883
Green Finance	0.974	0.975	0.981	0.929

4.2.2 Cross Loadings Test

Discriminant validity was further assessed using the cross-loadings criterion. According to CONG et al. (2025), an indicator should load higher on its associated construct than on any other construct in the model. This ensures that each indicator is more strongly related to its own construct than to others, thereby confirming that the constructs are empirically distinct.

As shown in Table 3, all indicators exhibit higher loadings on their respective constructs compared to other constructs. For instance, the indicators of carbon emissions (CE1–CE4) have very high loadings on the carbon emissions construct (ranging from 0.970 to 0.985), while their loadings on digital financial inclusion and green finance are comparatively lower. This pattern is consistently observed across all constructs and indicators, indicating that each measurement item is strongly associated with its intended construct.

Similarly, the indicators of digital financial inclusion (DFI1–DFI5) load highest on their respective construct (ranging from 0.914 to 0.948), while the green finance indicators (GF1–GF4) also demonstrate the highest loadings on the green finance construct (ranging from 0.948 to 0.979). Although some cross-loadings are relatively high, particularly between digital financial inclusion and green finance, they remain lower than the primary loadings of each indicator, thus satisfying the recommended criterion.

These results confirm that discriminant validity is established. The indicators cross loadings also be observed in Fig. 1, which visually illustrates the strength of the relationships between indicators and their respective constructs, further supporting the adequacy of the measurement model.

Table 3
Cross loadings test

CE1	Carbon Emission	Digital Financial Inclusion	Green Finance
	0.985	-0.895	-0.863
CE2	0.970	-0.881	-0.863
CE3	0.985	-0.892	-0.878
CE4	0.979	-0.884	-0.842
DFI1	-0.857	0.946	0.814
DFI2	-0.843	0.943	0.786
DFI3	-0.856	0.914	0.802
DFI4	-0.863	0.948	0.847
DFI5	-0.840	0.947	0.787
GF1	-0.847	0.828	0.969
GF2	-0.853	0.873	0.959
GF3	-0.818	0.768	0.948
GF4	-0.870	0.839	0.979

Figure 1: Indicator cross loadings

4.2.3 Multicollinearity Assessment (VIF)

Before evaluating the structural relationships, it is essential to assess multicollinearity among the predictor constructs.

Multicollinearity occurs when independent variables are highly correlated, which can distort path coefficients and affect model stability. In PLS-SEM, multicollinearity is assessed using the Variance Inflation Factor (VIF), where values below 5 (or more conservatively 3.3) indicate that multicollinearity is not a concern (Creutzig et al., 2023).

As shown in Table 4, the VIF values for all predictor constructs are below the recommended threshold of 3.3. Specifically, the VIF values for green finance and digital financial inclusion in predicting carbon emissions are within acceptable limits. Similarly, the VIF value for green finance in predicting digital financial inclusion is also below the threshold. These results confirm that multicollinearity is not a concern in this study. Therefore, the structural model estimates are reliable and can be interpreted with confidence.

Table 4
Collinearity Statistics (VIF)

Endogenous Construct	Predictor Construct	VIF
Carbon Emission	Green Finance	2.10
Carbon Emission	Digital Financial Inclusion	2.35
Digital Financial Inclusion	Green Finance	2.80

4.2.4 Discriminant Validity (Fornell-Larcker Criterion)

Discriminant validity was further evaluated using the Fornell-Larcker criterion. According to Nordgren (2023), discriminant validity is established when the square root of the Average Variance Extracted (AVE) for each construct is greater than its correlations with other constructs in the model. This criterion ensures that a construct shares more variance with its own indicators than with other constructs, thereby confirming that the constructs are empirically distinct.

As shown in Table 5, the diagonal elements represent the square roots of the AVE for each construct. The results indicate that carbon emissions (0.980), digital financial inclusion (0.940), and green finance (0.964) all have higher diagonal values compared to their respective inter-construct correlations.

For instance, the square root of AVE for carbon emissions (0.980) is greater than its correlations with digital financial inclusion (-0.907) and green finance (-0.879). Similarly, digital financial inclusion (0.940) exceeds its correlation with green finance (0.859). This pattern confirms that each construct is more strongly associated with its own indicators than with other constructs in the model.

Although the correlations among some constructs are relatively high, particularly between digital financial inclusion and carbon emissions, the Fornell-Larcker criterion is still satisfied because the diagonal values remain higher than the off-diagonal values. Therefore, the results provide strong evidence of discriminant validity.

Table 5
Fornell-Larcker Criterion

Construct	Carbon Emission	Digital Financial Inclusion	Green Finance
Carbon Emission	0.980		
Digital Financial Inclusion	-0.907	0.940	
Green Finance	-0.879	0.859	0.964

4.2.5 Discriminant Validity (Heterotrait-Monotrait Ratio – HTMT)

Discriminant validity was further assessed using the Heterotrait-Monotrait ratio (HTMT), which is regarded as a more robust and reliable method for evaluating discriminant validity in PLS-SEM (Miller et

al., 2025). According to recommended guidelines, HTMT values should be below 0.90 to confirm that constructs are empirically distinct (Jelinek, 2022).

As presented in Table 6, all HTMT values are below the acceptable threshold of 0.90. Specifically, the HTMT value between digital financial inclusion and carbon emissions is 0.828, while the values for green finance and carbon emissions (0.897), and green finance and digital financial inclusion (0.884) are also within the recommended limits.

These results indicate that the constructs are sufficiently distinct from one another and do not exhibit issues of discriminant validity. The moderate HTMT values further suggest that although the constructs are related, they capture different underlying concepts, which aligns with the theoretical framework of the study. The HTMT results provide strong evidence that discriminant validity is established, confirming the adequacy of the measurement model.

Table 6
Heterotrait-Monotrait Ratio (HTMT)

Construct Pair	Heterotrait-monotrait ratio (HTMT)
Digital Financial Inclusion <-> Carbon Emission	0.828
Green Finance <-> Carbon Emission	0.897
Green Finance <-> Digital Financial Inclusion	0.884

4.3 Structural Model Assessment

Following the validation of the measurement model, the next step involves the assessment of the structural model. The structural model evaluates the hypothesized relationships among the constructs, namely green finance (GF), digital financial inclusion (DFI), and carbon emissions (CE). This stage is essential for determining the strength, direction, and significance of the relationships proposed in the study. In PLS-SEM, the structural model is assessed using several key criteria, including collinearity diagnostics, path coefficients, coefficient of determination (R^2), effect size (f^2), and predictive relevance (Q^2) (Jawad et al., 2025). The significance of the hypothesized relationships is tested using the bootstrapping procedure, which provides t-values and p-values for hypothesis testing. This section therefore presents the results of the structural model evaluation, beginning with the assessment of collinearity, followed by hypothesis testing through path coefficients, and concluding with the evaluation of the model’s explanatory and predictive power.

4.3.1 Path Coefficients and Hypothesis Testing Results

The results presented in Table 7 provide strong empirical support for all the hypothesized relationships in this study. Specifically, H1, H2, H3, and H4 are all supported, indicating that the proposed conceptual framework linking green finance, digital financial inclusion, and carbon emissions is valid. The findings

not only confirm the statistical significance of the relationships but also provide meaningful insights into the mechanisms through which financial systems influence environmental sustainability.

With respect to H1, the results show that green finance has a significant negative effect on carbon emissions ($\beta = -0.383$, $t = 3.140$, $p = 0.002$), thereby supporting the hypothesis that green finance contributes to environmental improvement. This negative relationship suggests that increased allocation of financial resources toward environmentally friendly projects leads to a reduction in emissions. A possible explanation for this finding is that green finance facilitates investments in renewable energy, energy-efficient infrastructure, and low-carbon technologies, which directly reduce dependence on fossil fuels. Additionally, green financial policies may encourage firms and governments to adopt sustainable practices through incentives, regulations, and access to green funding.

Regarding H2, the findings reveal that green finance has a strong and positive effect on digital financial inclusion ($\beta = 0.859$, $t = 23.233$, $p < 0.001$), confirming that green finance significantly promotes financial inclusion through digital channels. This suggests that the expansion of green finance is closely linked to the development of digital financial infrastructure. One plausible explanation is that green finance initiatives often rely on innovative financial technologies such as mobile payments, digital lending, and fintech platforms to reach underserved populations. In the African context, where traditional banking infrastructure is limited, digital financial systems provide an efficient mechanism for distributing green funds and supporting small-scale sustainable investments.

In relation to H3, the results indicate that digital financial inclusion has a significant negative effect on carbon emissions ($\beta = -0.578$, $t = 4.627$, $p < 0.001$), supporting the hypothesis that increased financial inclusion contributes to environmental sustainability. This finding suggests that access to digital financial services enables individuals and businesses to invest in cleaner and more efficient technologies. A possible explanation is that digital finance reduces transaction costs, improves access to credit, and facilitates the adoption of renewable energy solutions such as solar home systems and clean cooking technologies. Furthermore, digital platforms enhance transparency and efficiency in financial transactions, which may reduce resource waste and promote sustainable consumption patterns.

Finally, the results support H4, which posits that digital financial inclusion mediates the relationship between green finance and carbon emissions. The indirect effect is negative and statistically significant ($\beta = -0.496$, $t = 5.200$, $p < 0.001$), indicating that green finance reduces carbon emissions through its positive influence on digital financial inclusion. The presence of both significant direct and indirect effects confirms partial mediation, suggesting that while green finance directly contributes to emission reduction, its impact is further strengthened through digital financial inclusion. This highlights the importance of digital financial systems as a transmission mechanism through which green finance achieves its environmental objectives. Overall, the results demonstrate that the interaction between green finance and digital financial inclusion plays a critical role in reducing carbon emissions. The findings underscore the need for integrated policy approaches that combine financial innovation with

environmental sustainability strategies, particularly in developing regions such as Africa where both financial inclusion and climate challenges are prominent.

Table 7
Path Coefficients

Hypothesis Relationship	Coef	T value	P value	2.5%	97.5%	Decision
Green Finance -> Carbon Emission	-0.383	3.140	0.002	-0.641	-0.153	Supported
Green Finance -> Digital Financial Inclusion	0.859	23.233	0.000	0.771	0.919	Supported
Digital Financial Inclusion -> Carbon Emission	-0.578	4.627	0.000	-0.790	-0.289	Supported
Green Finance -> Digital Financial Inclusion -> Carbon Emission	-0.496	5.200	0.000	-0.702	-0.301	Supported

4.3.2 Model Fit Assessment (SRMR)

The overall model fit was assessed using the Standardized Root Mean Square Residual (SRMR), which is a widely used goodness-of-fit measure in PLS-SEM. The SRMR represents the difference between the observed and predicted correlations, with lower values indicating a better model fit. According to Jaiswal (2025), an SRMR value below 0.08 is generally considered acceptable, while values closer to zero indicate a very good fit.

As presented in Table 8, the SRMR values for both the saturated model and the estimated model are 0.026. These values are well below the recommended threshold of 0.08, indicating an excellent model fit. The low SRMR values suggest that the discrepancy between the observed data and the model-implied data is minimal, thereby confirming that the model adequately represents the underlying data structure. The consistency between the saturated and estimated model SRMR values further indicates that the model is stable and well-specified. This provides additional confidence in the reliability of the structural model results and supports the validity of the conclusions drawn from the analysis.

Table 8
SRMR Results

	Saturated model	Estimated model
SRMR	0.026	0.026

4.3.3 Coefficient of Determination (R²)

The explanatory power of the structural model was assessed using the coefficient of determination (R²). The R² value represents the proportion of variance in the endogenous constructs that is explained by the exogenous constructs in the model. According to (Huynh & Nguyen, 2024; Iqbal et al., 2025), R² values of 0.75, 0.50, and 0.25 can be described as substantial, moderate, and weak, respectively.

As shown in Table 9, the R^2 value for carbon emissions is 0.860, with an adjusted R^2 of 0.854. This indicates that approximately 86% of the variation in carbon emissions is explained by green finance and digital financial inclusion. This can be considered a substantial level of explanatory power, suggesting that the model provides a very strong explanation of environmental outcomes.

Similarly, the R^2 value for digital financial inclusion is 0.738, with an adjusted R^2 of 0.733. This implies that about 73.8% of the variation in digital financial inclusion is explained by green finance. This value is also considered substantial, indicating that green finance is a strong predictor of digital financial inclusion in the model.

The small differences between the R^2 and adjusted R^2 values for both constructs suggest that the model is stable and not overfitted. Overall, these results demonstrate that the structural model has strong predictive accuracy and explanatory power, further supporting the robustness of the study findings.

Table 9
R-Squared Results

Carbon Emission	R-square	R-square adjusted
	0.860	0.854
Digital Financial Inclusion	0.738	0.733

4.3.4 Effect Size (f^2)

The effect size (f^2) was examined to assess the relative impact of each exogenous construct on the endogenous constructs in the model. The f^2 value measures how much an exogenous construct contributes to the R^2 value of an endogenous construct when it is included in the model. According to (Gu & Javed, 2025), f^2 values of 0.02, 0.15, and 0.35 indicate small, medium, and large effects, respectively.

As presented in Table 10, digital financial inclusion has a very large effect on carbon emissions ($f^2 = 0.625$), indicating that it is a strong predictor of environmental outcomes in the model. This suggests that digital financial inclusion plays a critical role in reducing carbon emissions, supporting the earlier finding that it significantly influences environmental sustainability.

Green finance also demonstrates a moderate to large effect on carbon emissions ($f^2 = 0.275$), indicating that it contributes meaningfully to explaining variations in carbon emissions. This further confirms the importance of green finance as a driver of environmental performance.

In addition, green finance exhibits an extremely large effect on digital financial inclusion ($f^2 = 2.823$), which is substantially higher than the conventional threshold for a large effect. This indicates that green finance is the dominant predictor of digital financial inclusion in the model. The magnitude of this effect suggests that changes in green finance strongly influence the level of digital financial inclusion, reinforcing the earlier finding of a strong positive relationship between the two constructs. The effect

size results indicate that both green finance and digital financial inclusion have substantial impacts on the endogenous constructs, with digital financial inclusion playing a particularly strong role in explaining carbon emissions, and green finance being the primary driver of digital financial inclusion.

Table 10
Effect Size (f²)

Carbon Emission	Carbon Emission	Digital Financial Inclusion	Green Finance
Digital Financial Inclusion	0.625		
Green Finance	0.275	2.823	

4.4 Discussion of Key Findings

Green Finance and Carbon Emissions

The results of the study reveal that green finance has a significant negative effect on carbon emissions, thereby supporting H1. This finding indicates that an increase in green finance leads to a reduction in carbon emissions in the African context. Theoretically, this result is consistent with Financial Intermediation Theory, which posits that financial systems influence economic and environmental outcomes through efficient allocation of capital. In this case, green finance channels financial resources toward environmentally sustainable projects such as renewable energy, energy efficiency, and low-carbon infrastructure, thereby reducing environmental degradation.

This finding aligns with prior empirical studies (Zhang et al., 2026; Zhu et al., 2023), which emphasize the role of green finance in improving environmental quality. However, it contrasts with studies such as (Xiao et al., 2024; Xu & Wang, 2025), which report weaker or insignificant effects in developing economies due to institutional inefficiencies and underdeveloped financial markets. The stronger effect observed in this study may reflect the increasing effectiveness of green finance initiatives in Africa, supported by growing policy commitment and international climate funding. The implication of this finding is that policymakers should strengthen green finance mechanisms by improving regulatory frameworks, expanding green investment instruments, and enhancing access to sustainable financing. Such efforts can significantly accelerate the transition toward a low-carbon economy.

Green Finance and Digital Financial Inclusion

The findings further indicate that green finance has a strong and positive effect on digital financial inclusion, thus supporting H2. This suggests that the expansion of green finance contributes significantly to the development of digital financial systems. From a theoretical perspective, this relationship can be explained using the Diffusion of Innovation Theory, which emphasizes that innovations are more effectively disseminated through enabling technological systems. Green finance,

as a financial innovation, is increasingly delivered through digital platforms, thereby promoting financial inclusion.

This finding is consistent with studies by (Tsybuliak et al., 2025; Wu et al., 2026), which highlight the transformative role of digital finance in expanding financial access. However, unlike earlier research that treats green finance and financial inclusion as separate constructs, this study demonstrates a strong direct linkage between the two. This represents an important contribution by showing that sustainability-oriented finance can drive digital financial development. The implication is that policymakers should integrate green finance strategies with digital financial infrastructure development. Leveraging digital platforms can improve the accessibility and effectiveness of green finance, particularly among underserved populations.

Digital Financial Inclusion and Carbon Emissions

The results also show that digital financial inclusion has a significant negative effect on carbon emissions, thereby supporting H3. This finding suggests that increased access to digital financial services contributes to environmental sustainability by reducing emissions. Theoretically, this relationship can be explained through both Financial Intermediation Theory and Diffusion of Innovation Theory, as digital financial systems facilitate access to financial resources and support the adoption of environmentally sustainable technologies.

This finding aligns with emerging literature (Tang et al., 2026; Teixeira, 2026), which indicates that financial inclusion can enhance environmental performance. However, it contrasts with studies such as (Singh et al., 2026; Surwanti et al., 2026), which argue that digitalization may increase environmental pressure due to higher energy consumption from digital infrastructure. The negative relationship observed in this study suggests that, within the African context, the environmental benefits of digital financial inclusion outweigh its potential costs. This may be due to its role in enabling access to clean energy solutions, improving efficiency, and reducing transaction-related resource waste. The implication is that digital financial inclusion should be promoted as part of environmental sustainability strategies. Policymakers should ensure that digital financial systems are aligned with green initiatives to maximize their environmental benefits.

Mediating Role of Digital Financial Inclusion

Finally, the results confirm that digital financial inclusion significantly mediates the relationship between green finance and carbon emissions, thereby supporting H4. This indicates that green finance reduces carbon emissions not only directly but also indirectly through digital financial inclusion. The presence of partial mediation suggests that digital financial inclusion serves as an important transmission mechanism through which green finance achieves its environmental objectives.

From a theoretical standpoint, this finding integrates Financial Intermediation Theory and Diffusion of Innovation Theory, demonstrating that financial resources are more effective when supported by

technological delivery systems. Digital financial inclusion enhances the reach and efficiency of green finance by reducing transaction costs, improving accessibility, and facilitating the adoption of sustainable technologies.

This finding extends the existing literature by (Ogunmola, 2026; Rani et al., 2025) providing empirical evidence on the interaction between green finance and digital financial inclusion, which has been largely overlooked in previous studies. While prior research has focused on their individual effects, this study demonstrates how their combined influence enhances environmental sustainability (Bayong et al., 2025; Mori, 2026). The implication is that policymakers should adopt an integrated approach that simultaneously promotes green finance and digital financial inclusion. Such a strategy can significantly enhance the effectiveness of environmental policies and accelerate progress toward sustainable development.

5. Conclusion, Policy Recommendations, and Limitations

5.1 Conclusion

In recent years, the increasing threat of climate change has intensified the need for sustainable development strategies, particularly in developing regions such as Africa. Despite contributing minimally to global greenhouse gas emissions, African countries remain highly vulnerable to environmental degradation and climate-related risks. At the same time, the continent faces significant development challenges, including limited access to energy and financial services. In this context, green finance and digital financial inclusion have emerged as critical mechanisms for promoting both economic development and environmental sustainability. However, the extent to which these two systems interact to influence carbon emissions remains insufficiently explored. Against this backdrop, this study examined the relationship between green finance, digital financial inclusion, and carbon emissions across 48 African countries, with a particular focus on the mediating role of digital financial inclusion. Using Partial Least Squares Structural Equation Modeling (PLS-SEM), the study analyzed both the direct and indirect effects of green finance on environmental outcomes. The findings reveal that green finance has a significant negative effect on carbon emissions, indicating that increased investment in environmentally sustainable financial instruments contributes to emission reduction. The results also show that green finance significantly promotes digital financial inclusion, highlighting the strong link between financial sustainability and financial innovation. Furthermore, digital financial inclusion was found to have a significant negative effect on carbon emissions, suggesting that improved access to digital financial services enhances environmental sustainability. Most importantly, the study confirms that digital financial inclusion partially mediates the relationship between green finance and carbon emissions. This implies that green finance not only directly reduces emissions but also does so indirectly by enhancing digital financial inclusion, which improves access to sustainable technologies and financial services. From a theoretical perspective, the study contributes to the literature by integrating Financial Intermediation Theory and Diffusion of Innovation Theory, demonstrating that financial resources are more effective when supported by technological delivery systems. Empirically,

the study extends existing research by providing evidence from a broad sample of 48 African countries, thereby enhancing the generalizability of the findings in a developing economy context. In terms of implications, the findings underscore the importance of adopting integrated strategies that combine green finance with digital financial inclusion. Policymakers should focus not only on increasing green financial investments but also on strengthening digital financial infrastructure to maximize environmental benefits. Overall, the study concludes that the synergy between financial sustainability and digital innovation is essential for achieving long-term environmental sustainability in Africa.

5.2 Policy Recommendations

Building on the findings of this study, several policy recommendations are proposed to enhance environmental sustainability through the effective integration of green finance and digital financial inclusion across African countries.

First, there is a need to strengthen green finance frameworks to ensure a sustained flow of capital toward environmentally sustainable projects. Governments and regulatory authorities should promote the development of green financial instruments such as green bonds, climate funds, and sustainable investment portfolios. In addition, policy incentives such as tax reliefs, subsidies, and risk-sharing mechanisms should be introduced to encourage private sector participation in green investments. Strengthening these frameworks will enhance the capacity of financial systems to support low-carbon development. Second, policymakers should prioritize the expansion of digital financial infrastructure, particularly in rural and underserved areas. Investments in mobile banking systems, digital payment platforms, and fintech innovations are essential for improving financial access and inclusion. Given the strong relationship between digital financial inclusion and environmental sustainability identified in this study, expanding digital financial systems will not only improve financial access but also enhance the effectiveness of green finance initiatives. Third, an integrated policy approach should be adopted to simultaneously promote green finance and digital financial inclusion. The findings of this study demonstrate that these two systems are highly complementary, with digital financial inclusion acting as a key channel through which green finance influences environmental outcomes. Therefore, policymakers should leverage digital platforms to deliver green financial products, such as financing renewable energy solutions, supporting pay-as-you-go solar systems, and facilitating access to clean cooking technologies. Such integration will maximize the environmental impact of financial policies. Fourth, there is a need for capacity building and financial literacy programs to enhance awareness and adoption of green finance and digital financial services. Many individuals and small businesses lack sufficient knowledge of sustainable financial products and digital financial tools. Educational initiatives and targeted awareness campaigns can improve adoption rates and ensure that financial innovations translate into tangible environmental benefits. Fifth, governments should focus on strengthening institutional quality and governance frameworks to support both financial innovation and environmental sustainability. Transparent regulatory systems, effective financial oversight, and stable macroeconomic environments are essential for ensuring the success of green finance and digital financial inclusion initiatives. Without strong institutions, the effectiveness of these policies may be limited. The key policy

implication of this study is that isolated interventions are insufficient. Instead, a coordinated and integrated approach that combines financial sustainability with digital innovation is necessary to effectively address climate change challenges in Africa.

5.3 Limitations and Future Directions

Despite its significant contributions, this study is subject to several limitations that should be considered when interpreting the findings.

First, the study is based on cross-sectional data from 48 African countries, which limits the ability to capture temporal dynamics and long-term causal relationships. While the findings provide valuable insights into the relationships among the variables, they do not account for changes over time. Future research could employ panel or longitudinal data to better understand the dynamic interactions between green finance, digital financial inclusion, and carbon emissions. Second, the study focuses on a specific set of constructs, namely green finance, digital financial inclusion, and carbon emissions. Although these variables are central to the research, other important factors such as institutional quality, energy structure, technological advancement, and regulatory policies were not explicitly included in the model. The omission of these variables may limit the comprehensiveness of the analysis. Future studies should incorporate additional variables to provide a more holistic understanding of environmental sustainability. Third, the measurement of constructs was based on selected indicators, which may not fully capture the multidimensional nature of green finance and digital financial inclusion. While the indicators used in this study are widely accepted, they may not reflect all aspects of these complex constructs. Future research could explore alternative measurement approaches or include additional indicators to enhance robustness. Fourth, the study is context-specific to Africa, which may limit the generalizability of the findings to other regions. Although the African context provides valuable insights due to its unique combination of financial exclusion and climate vulnerability, the results may differ in developed economies with more advanced financial and institutional systems. Therefore, caution should be exercised when extending these findings to other contexts. Finally, although PLS-SEM is an appropriate and widely used method for analyzing complex relationships and mediation effects, it is primarily a predictive technique and does not establish strict causality. As such, the results should be interpreted as associations rather than definitive causal relationships. Future research could employ alternative econometric techniques to strengthen causal inference and validate the findings.

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Figures

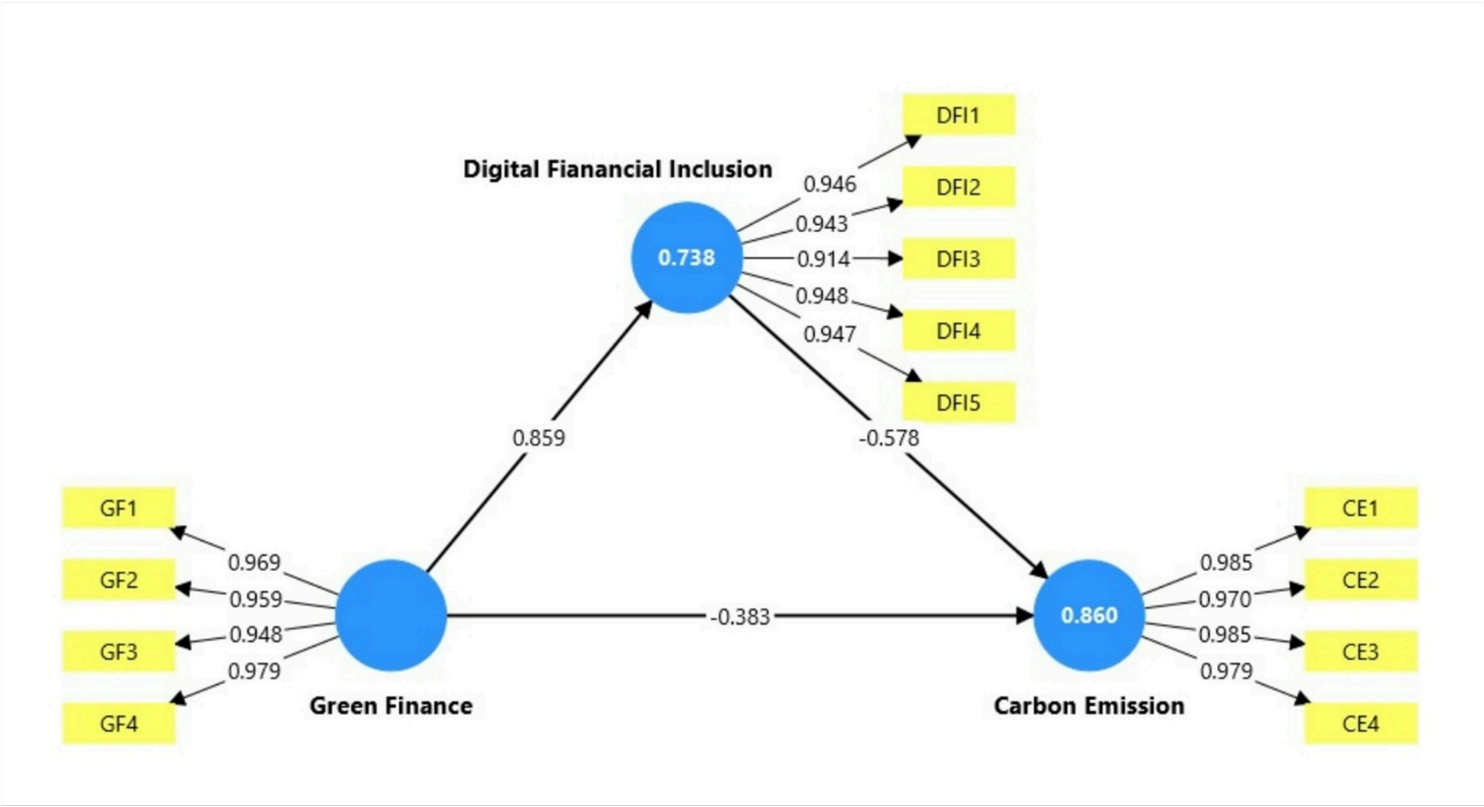


Figure 1

