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Research article

The nexus of green finance and financial efficiency in Sub-Saharan Africa

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Abstract: This paper explores the nexus of green finance and financial efficiency in Sub-Saharan African nations from 2011 to 2024. The autoregressive distributed lag technique is applied for the results estimation. The variables include environmental protection expenses, carbon footmark of bank credits, and green bonds as exogenous variables. Financial efficiency was the endogenous variable. The research shows that environmental protection expenses positively influences financial efficiency via enhancing market stability and investor confidence. The carbon footmark of bank credits negatively impacts financial efficiency. Green bonds insignificantly affect financial efficiency because of the weak green finance market. The governments should strengthen green funding projects by expanding the green bonds' market via tax incentives for sustainable investments and enforce environmental sustainability goals regulations to enhance financial efficiency. The research increases literature on the link between environmental protection expenses and its influence on financial efficiency. Financial institutions should be incentivized to reduce carbon-intensive investments. Additionally, strict enforcement of environmental regulations, the introduction of carbon pricing mechanisms, and institutional governance reforms to ensure the effective execution of green finance. These measures will foster a sustainable financial ecosystem, promoting long-term economic stability and sustainability in Sub-Saharan African financial markets.

Key words: green finance; financial efficiency; Sub-Saharan Africa

JEL Codes: G1, G2,Q2, Q5

1. Introduction

The capital markets efficiencies are vital to achieve Sub-Saharan African (SSA) countries' economic growth. It enhances capital allocation, expands investment opportunities, and strengthens financial stability (Beck et al., 2011). Generally, the SSA capital market efficiency is low, with noticeable underdeveloped capital markets, illiquidity, and limited long-term financing. Although there are some improvements in technology and banking sector reforms mostly in Anglophone countries (IMF, 2022a). Furthermore, inefficient credit allocation, weak institutions, and high interest rates contribute to limited economic growth despite the financial development efforts. Country wise, the Nigerian financial sector reforms, such as the recapitalization of banks improved market efficiency, reduce systemic risks and enhance credit accessibility (Marbuah, 2020).

Efficient financial markets lower transaction costs and information asymmetry. It fosters entrepreneurship and business expansion as seen in Kenyan M-Pesa revolution which boosted financial inclusiveness and small business financing (Nyasha & Odhiambo, 2019). Additionally, financial efficiency entices foreign investments and stimulates infrastructure development as demonstrated by the substantial investments in the Ethiopian industrial parks. It strengthens monetary policy transmission and ensures economic stabilization evident in South African inflation-target framework that enhances stable prices and investor confidence (Nyasha & Odhiambo, 2019).

Green finance is critical in improving financial markets' efficiency as it encourages sustainable investments and mitigates environmental concerns. Recently, climate resilient infrastructures have been financed by green bonds in Nigeria. Therefore, it strengthens market stability and investor trust. Similarly, the sustainability segment that promotes green bonds listings in South Africa is luring investments in renewable energy and eco-friendly sectors (UNEP, 2020). Green financial instruments in Kenya reduce borrowing costs and risk-adjusted return. It is drawing local and global investors to join the renewable energy industry (World Bank, 2022). Green finance reduces financial volatility associated with climate variations through environmental risk assessments (Scholtens, 2020). Green finance has an influence on financial market efficiencies as it improves the efficiency and channels investments into sustainable projects. Green finance funds renewable energy and climate adaptation initiatives (UNEP, 2021). Environmental degradation threatens market stability by increasing credit risks and discourages long-term investments. The Madagascan deforesting process and extreme weather conditions have disrupted agricultural financing systems (World Bank, 2022). Severe climate-related risks exacerbate liquidity constraints which lead to cautious lending in environmentally fragile industries (OECD, 2021).

Sustainable banking policies in the Ethiopian green growth strategy are improving financial intermediation efficiency. This matches loan allocation to environmentally friendly initiatives to foster inclusive economic growth (IMF, 2022). Furthermore, the green microfinance in Uganda has given small-scale farmers access to climate-smart agricultural financing which increases economic resilience (IFC, 2021). As the SSA green finance is growing, the capital markets gain competitiveness by complying with global sustainability norms (Sachs et al., 2020). Efficient green financial markets could mitigate systemic risks and enhance economic stability (OECD, 2021).

The significance of green finance in determining the effectiveness of financial markets cannot be underrated. Extreme weather events, including climate change-induced disasters (e.g., rain fall, inundations, and deforestation), disrupt economic activities, reduce investor confidence, and limit capital inflows (World Bank, 2022). This leads to higher insurance payments and borrowing costs, making financial markets less efficient to allocate resources to productive sectors (OECD, 2021). This is because destruction of properties and resources weaken economic diversification; increase dependence on volatile commodity markets and reduce the efficiency of the financial markets (UNEP, 2021). Hence, without proactive green finance policies, environmental degradation aggravates financial volatility. Prior studies omit to holistically evaluate the synergy of green finance and financial markets efficiency in the African nations like in this study.

Although, SSA countries account for a minor share of global greenhouse gas emissions but are among the most severely impacted nations by climate change. They require an estimated $2.9 trillion by 2050 for sustainable development (World Bank, 2022). Green financing mechanisms are high perceived investment risks which deter private sector involvement. Further investigation is needed to determine how green finance impacts financial efficiency like reducing non-performing loans, improving capital allocation in the high-risk environment. Many SSA nations are limited in robust institutional frameworks, transparent reporting mechanisms, and tailored green financial products required to package and manage sustainable projects effectively.

Hence, the relationship between green finance and financial efficiency is highly conditional on institutional quality. The literature should investigate how weak regulatory environments distort this relationship. What governance thresholds are required to ensure that green investments do not compromise overall financial stability. The SSA financial sector is characterized by a mix of deep informal credit markets, expanding digital financial technologies, and traditional banking systems (IMF, 2022). It remains unclear how integrating green finance, such as green bonds, affects the efficiency of the financial system. Investigating if green finance catalyzes financial inclusion or strains the already limited liquidity in SSA financial markets is critical for policymakers. The previous literature on green finance focuses primarily on advanced economies. Existing empirical findings on the green finance-efficiency nexus in SSA are mixed. Sometimes, it is fragmented and cannot be generalized across different levels of economic development within the continents. A focused investigation is needed to establish context-specific policies.

From literature, different studies measured financial efficiency variedly. This research measures financial efficiency using the financial markets index. The results are all debatable. Some studies present positive links while others give negative relationships between green finance and financial efficiency. Existing African green finance studies provide limited evidence on the dynamic interaction between green finance and findings, especially in Sub-Saharan Africa under heterogeneous conditions. This study addresses that gap. This paper evaluates the nexus of green finance and the SSA nations' financial markets' efficiency.

2. Review of literature

This study is anchored on the efficient market hypothesis (EMH) propounded by Fama (1970). The theory hypothesizes that financial markets efficiently mirrors all the existing market information. Hence, it is difficult to steadily accomplish greater returns by taking advantage of mispriced assets (Fama, 1970). The theory affirms that market prices adjust swiftly and accurately to both privately and publicly provided information. Since all accessible information is embedded in asset prices, investors find challenges to constantly overtake the market through trading strategies. The EMH classifies market efficiency into three forms: weak-form, semi-strong-form, and strong-form efficiency. Weak-form efficiency suggests that existing prices wholly reveal all preceding prices and volume data, rendering technical analysis ineffective in generating consistent excess returns. Semi-strong-form efficiency asserts that asset prices incorporate all the public accessible information. It implies that fundamental analysis based on financial reports and news cannot provide any advantage (Fama, 1991). Strong-form efficiency postulates that market prices integrate altogether the publicly and privately accessible information. This makes it difficult for any market participant, including insiders, to regularly realize superior returns.

The EMH explains how financial markets incorporate environmental and sustainability-related information into investment decisions, thereby influencing the allocation of capital toward green investments. Green finance theory extends this mechanism by emphasizing the role of sustainable financial instruments in channeling resources toward environmentally responsible projects. The green finance model is rooted from the broader context of sustainable finance. The green finance model is rooted from the broader context of sustainable finance. This development of the theory was led by the United Nations Environment Program Finance Initiative (UNEP FI), established in 1992. Key foundational frameworks were later developed by the Climate Bonds Initiative in 2014 through the Paris Agreement. The theory aligns capital markets to ecological, communal, and governance criteria. The model posits that the financial sector mobilizes funds to promote sustainable environmental projects in areas, such as waste management, renewable energy, pollution reduction, and energy efficiency initiatives (Wang et al., 2024). This hypothesis is associated with the dual dividend model, which claims that green investments and environmental taxes usually produce two benefits. That is to diminish environmental damage and simultaneously boost economic efficiency. This framework is a mechanism that channels resources away from environmentally harmful activities to those that support sustainability. Therefore, the theory helps to mitigate the adversities of climate change alongside environmental degradation.

Environmental Kuznets curve (EKC) model theorizes that an inverted-U association between growth and environmental degradation. Green finance crucially promotes sustainable development as it facilitates the change to low-carbon economies (Lin et al., 2024). This theory shows that as the capital market expands, the economies develop and that pollution initially rises but ultimately declines when a country reaches a higher income level and invests more on environmental protection. The EKC hypothesis provides the macroeconomic linkage which explains how economic growth, supported by green financial allocation, may initially increase environmental degradation but eventually contribute to environmental improvement after a certain developmental threshold is reached. Accordingly, the integrated framework puts green finance as the transmission mechanism through which efficient financial markets influence environmental outcomes along the EKC pathway.

Thus, green finance accelerates the transition by funding green technologies and infrastructure. Consequently, the economies are shifted toward cleaner growth models in their development process (Dong et al., 2024). This theory emphasizes the role of financial instruments, such as green bonds, green loans, and investments, in reducing the carbon footmark of economic activities, particularly in emerging economies. In summary, the EMH, green finance theory, and the environmental Kuznets curve collectively provide a robust basis for modern sustainability and economic research models. They explain how market information, financial systems' mechanisms, and macroeconomic development interconnect to reduce environmental degradation.

2.1. Empirical reviews

Schumacher et al. (2020) examined the influence of sustainable finance and Japanese investments using the generalized method of moment. The financial sector's institutions are exposed to significant climate risks from both inside and outside Japan. Urban and Wójcik (2019) investigated the investment banks' sustainability integration into the underwriting services. The findings displayed that investment banks patronize underwriting companies that are identified for major governance, environmental, and social misconduct. The investment banks do not restrain from underwriting companies that provide contentious products. Ozili (2021) extends solutions that can make finance sustainable by stating that greater focus should be on the ways various funding subsidizes sustainability. Also, he stated that light-touch regulations need to propagate the small sustainable finance sector. The bottom-up approach is appropriate for the sustainability of the finance sector. Shabb et al. (2021) revealed that the finance sector plays an increasing transitional role in the sustainable development by incorporating sustainability into their financial analysis and investment portfolios.

Schoenmaker & Schramade (2018) showed that financial establishments are avoiding unmanageable corporations from various risks perspectives. Financial institutions invest in sustainable businesses and development schemes to create long-term value for the community. Partridge and Medda (2020) established that a green municipal bond index outperformed the closest similar Standard & Poor index from 2014 to 2018. Maria et al. (2023) advocated that climate-related financial hazards, green bonds, and resource model advancements are the breakthroughs. Fu et al. (2023) proposed that it is desirable for green financing to support effective policies and technological innovation to harmonize clusters, communities, and systems for sustainability via the timely use of renewable and sustainable energy facilities that are beneficial to the future. Cui et al. (2020) examined the link between green finance and sustainable development in China using the autoregressive distributed lag method. The results stated that green investment encourages sustainable development and cleaner production. Jena and Dhruba (2020) studied the role of green financial services on the Indian economic development. The findings revealed an increasing necessity to explain the financial sector's benefits from green finance. Marbuah (2020) explored the significance of green bonds in the African capital markets using the fully modified ordinary least square. The findings showed that modest growth exists in the capital market due to green finance services. Tolliver et al (2021) investigated the effect of green financial products on the Asian sustainable economic development from 1990–2020. The results showed that green finance increased as the demand for sustainable development grows.

Ren et al. (2020) examine the effect of green financial services on carbon intensity in China. The findings showed that the green financial index is significantly associated with a reduction in carbon intensity. Acheampong et al. (2020) examined the link of financial market depth and carbon dioxide emission in emerging countries. The findings presented a negative link of financial market depth and carbon dioxide emissions in emerging financial markets. Also, the results showed a positive effect of market bonds on carbon dioxide emissions in frontier financial markets. Samour et al. (2019) investigated the impacts of banking sector development on the Turkish carbon dioxide emissions from 1995–2018 using econometric cointegration. The results display that the Turkish banking sector boosts carbon dioxide emissions which worsens environmental quality. Renzhi and Baek (2020) studied the association between financial inclusion and environmental quality. The findings revealed an overturned U-shaped link of financial inclusion and environmental quality.

Paramati et al. (2020) posit that in the member countries of the Organization for Economic Cooperation and Development financial deepening worsens environmental quality by raising carbon dioxide emissions. Shahbaz et al. (2016) examined the link of financial development on environmental sustainability in Pakistan from 1985–2014 using the correlation matrix. The results observed that financial development negatively affects environmental sustainability. This leads to increased carbon dioxide emissions. Using the generalized method of moment, Ibrahim and Law (2016) evaluated the influence of financial sector development and commercial services on carbon dioxide emissions in selected African nations between 2000 and 2010. The findings indicated that financial development negatively affects environmental sustainability. Saidi and Mbarek (2017) studied the effect of per capita income, urbanization, and financial development on the environmental sustainability in emerging economies. The results showed that financial development is positively linked to environmental sustainability. It leads to a decrease in carbon dioxide emissions.

Charfeddine and Kahia (2019) evaluated relationship between financial development and economic growth in the MENA region. The findings displayed an insignificant influence on carbon dioxide emissions. Seetanah et al. (2019) examined the impact of financial development on carbon dioxide emissions. The study concluded that financial development insignificantly impacts carbon dioxide emissions. Ngong et al. (2022a) explored the link between greenhouse gas radiations and poverty reduction in the ECOWAS from 1985–2020 applying the autoregressive distributed lag and Granger causality tests. Carbon dioxide showed an insignificant positive link to gross domestic product. Nitrous oxide relates positively to the gross domestic product per capita. Methane negatively relates to gross domestic products. Ngong et al. (2022b) scrutinized the affiliation of urbanization to carbon dioxide emissions in the Central African Economic and Monetary Community between 1990 and 2019 using the fully modified and dynamic ordinary least squares. Urbanization significantly and positively relates to carbon dioxide emissions. Carbon dioxide granger causes urbanization unit directionally.

From literature, some studies report positive results (Ngong et al., 2022b; Saidi and Mbarek, 2017). Others show negative findings (Ibrahim and Law, 2016; Shahbaz et al., 2016) and some give insignificant effects of green finance on environmental outcomes Ozili (2021). These inconsistencies exist possibly due to institutional quality, market maturity, and differences in econometric approaches.

3. Methodology

This study used data from the following SSA nations: Angola, Botswana, Ghana, Mauritius, Mozambique, Nigeria, Senegal, South Africa, Tanzania, Uganda, and Zambia. These countries are chosen based on data availability from 2011 to 2024. This study employed the autoregressive distributed lag (ARDL) method. The ARDL effectively handles minor samples and provides efficient estimates even with mixed-order integrated variables. The ARDL is the preferred technique because it is simple and flexibly applied. It generates an error correction model (ECM) using linear transformation and consider estimates regardless of their sample size, which can either be small or finite (Manasseh et al., 2018). It can simultaneously estimate long-run and short-run cointegrating relationships to provide unbiased estimates.

Using standard ordinary least square (OLS) on non-stationary time series often results in values that are highly significant but are misleading. ARDL includes lags of variables to properly model data-generating processes and prevent spurious issues. Standard OLS estimators in time-series frameworks suffers from endogeneity. ARDL includes sufficient lags that neutralize residual correlation and endogenous regressors. Traditional cointegration methods require all variables to be integrated at the exact same order necessitating tedious unit root pre-testing. The ARDL handles a mix of I(0) and I(1) variables with no need for prior unit root tests. Prior studies erroneously omit to access holistic evaluation of the synergy among green finance and financial efficiency especially in Africa countries.

This study measures financial effectiveness with the financial market efficiency index (FMEI). The financial market efficiency index is built via a composite or multi-layer efficiency model by aggregating the values using principal component analysis. First, autocorrelation test is done to measure whether past returns predict future returns for weak-form efficiency. Second, a check for long-term random walk behavior in prices. Third, variance ratio tests are conducted to test random walk hypotheses across multiple time lags.

Green finance is measured using environmental protection expenses (EPEXP), carbon footmark of bank loans (CFBL), and green bonds (GRB). The carbon footmark of bank loans variable is used to capture the environmental impact associated with bank-financed economic activities. It is constructed by linking bank credit allocation to carbon-intensive sectors with the sectoral carbon dioxide emission indicators. The variable is calculated by estimating the proportion of total bank lending directed toward high-emission sectors, such as energy, transportation, manufacturing, and extractive industries. The carbon footprint of bank loans or financed emissions is calculated by multiplying the outstanding loan amount by the borrower's total emissions, adjusted by an attribution factor. The loan amount is divided by the company's total equity and debt. This method attributes emissions based on the proportion of the bank's financing in the borrower's total capitalization:

$$\text{Attribution Factor} = \frac{\text{Outstanding amount of loan}}{\text{Total equity} + \text{Debt of borrower}}$$

$$\text{Financed Emissions} = \text{Attribution Factor} \times \text{Borrower annual emissions}$$

The index reflects the extent to which the banking sector credit contributes to carbon-generating economic activities. This study is controlled by the ratio of broad money and gross domestic product (M_2/GDP) and exchange rate (EXR). Table 1 below presents the definition of the model variables.

Table 1. Definition of variables.

Acronyms	Definition	Repository
FMEI	Financial market efficiency index	https://prosperitydata360.worldbank.org/en/indicator/IMF+FDI+FD_FI_IX
EPEXP	Environmental protection expenditure	https://shorturl.at/vlAcm
CFBL	The carbon footprint of bank loans	https://bit.ly/4a4qVmV
GRB	Green bonds	https://shorturl.at/vnFmj
M_2/GDP	Ratio of broad money and GDP	https://data.worldbank.org/indicator/FM.LBL.BMNY.GD.ZS and https://data.worldbank.org/indicator/NY.GDP.MKTP.CD
EXR	Exchange rate	https://data.worldbank.org/indicator/PA.NUS.FCRF

Source: Researcher's Conception

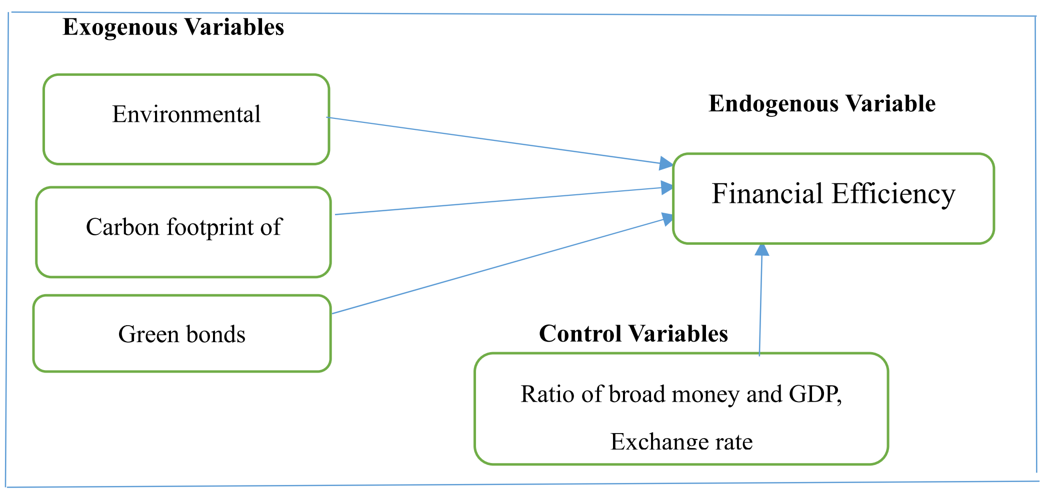

Figure 1. Conceptual framework.

Source: Author's conception

This paper follows Manasseh et al. (2024) to use the panel dynamic autoregressive distributed lag. The panel dynamic model to capture the relationships is as shown below.

$$FMEI = \phi_0 + \phi_{1x1} + \cdots + \phi_{pxt-p} + \beta_{0zt} + \beta_{1zt-1} + \cdots + \beta_{qzt-q} + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

here xt is the autoregressive term, Z_t is the regressors' distributive share, and ε_t is the error term. Introducing the green finance variables, model (1) is transmuted to Equation (2) as

$$FMEI_i = \phi_i, + \beta_t Q_i, + \rho_t R_i, + ti = 1\ldots \quad t = 1,..T\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

where T is the time, $FMEI_i$ is the financial market efficiency index, Q_i is the exogenous variables' vector, R_i is control variables' vector, ϕ_i & t are the intercept and error term, respectively, and β_t and ρ_t are the independent and control variables' coefficients, respectively. For an ARDL (1, 1) model, the Akaike information criterion (AIC) lag length criterion is the most suitable. It is widely used especially if the dataset is small. The AIC is preferred because it imposes a lower penalty on additional lags, which minimizes the chance of underestimating the true lag length. Converting Equation (2) into an ARDL (1, 1) linear equation, gives Equation (3) as follows:

$$FMEI_{it} = \phi + \pi \Delta FMEI_{it-1} + \beta \Delta Q_{it-1} + \rho_t \Delta R_{it-1} + \lambda GF_{it-1} + \gamma Q_{it-1} + \xi R_{it-1} + \vartheta_{it}\ldots\ldots\ldots \text{(3)}$$

where $FMEI_{it-1}$ is the lag of the dependent variable, GF denotes the green finance variables; Q_{t-1} and R_{i-1} are the explanatory and control variables' vectors; Δ indicates the variables difference operator; ϑ_{it} denotes the stochastic terms; λ, γ, and ξ stand for the coefficient of the model's long-term relationship; and π, β, and ρ signify the short-run dynamics coefficients. The following basic econometric tests were performed: normality, serial correlations, Ramsey test, heteroscedasticity test, Hausman test, descriptive statistics, correlation test, and unit root tests. The tests aided in making decisions concerning the variables and models to use.

4. Results and discussion

Data description is sacrosanct in panel studies especially in time series data. It is helpful to ascertain the characteristics of the data using the procedures of central tendencies. From Table 2, the values of mean, median, standard deviation, skewness, and kurtosis for the variables do not drift greatly from each other. The variations in the series move from −136.1 to 9.98 which represent the lowest and highest values in the series. The Jarque-Bera probability values for all the variables are less than 0.05. This means the null hypothesis of normality is rejected the variables are not normally distributed. Robustly, small samples are exclusively vulnerable because non-normality has a stronger effect when the sample size is limited. However, the method used is relatively robust to moderate non-normality, particularly in the estimation of small samples. Also, the skewness of data may distort the regression coefficients. The kurtosis increases the likelihood of the extreme observations which affects the inferential accuracy of the data. Therefore, it is suitable for the analysis of the relationships between green finance and financial efficiency.

From Table 3, the Spearman's correlation test is a non-parametric measure to assess the strong suit and direction of a monotonic relationship between two variables is used. It ranks data rather than raw values to make it suitable for ordinal or non-normally distributed data. The environmental protection expenses negatively correlate with financial market efficiency index. Green bonds positively correlate with financial market efficiency index. The carbon footprint of bank loans positively correlates with financial market efficiency index. Financial deepening positively relates with financial market efficiency index. A weak correlation exists among the exchange rate and financial market efficiency index. This suggests that exchange variations timidly influence financial market efficiency.

Table 2. Descriptive statistics.

	FMEI	EPEXP	CFBL	GRB	M2/GDP	EXR
Mean	42.44	2.121	−0.003	0.785	1.208	−1.690
Median	7.622	3.056	0.172	0.714	0.868	−6.059
Maximum	1.731	10.61	4.144	8.801	9.980	2.272
Minimum	0.000	−5.181	−36.47	−2.196	−9.437	−136.1
Std. Dev.	46.22	3.115	5.196	1.058	2.192	46.16
Skewness	0.545	−0.126	−0.157	1.279	−0.281	1.279
Kurtosis	1.534	2.845	15.72	12.08	4.926	7.857
Jarque-Bera	91.66	2.337	4449.	2446.	110.5	827.5
Probability	0.000	0.030	0.000	0.000	0.000	0.000
Observations	659	659	659	659	659	659

Source: Conceptualized by the Researcher.

Table 3. Correlation results.

	FMEI	EPEXP	CFBL	GRB	M2/GDP	EXR
FMEI	1.000					
EPEXP	−0.0947	1.000				
CFBL	0.0662	−0.276	1.000			
GRB	0.0893	0.044	−0.421	1.000		
M2/GDP	0.0642	0.560	−0.017	0.075	1.000	
EXR	0.097	0.173	0.531	0.583	0.223	1.000

Source: Conceptualized by the Researcher.

Table 4. Unit root test.

Variable	LLC	IPS	Fisher-ADF	Fisher-PP	Order of Integration	
					Level	First Diff.
FMEI	−12.65***	−3.599***	173.6***	168.4***		
	(0.000)	(0.000)	(0.000)	(0.000)	I(0)	
EPEXP	−7.753***	−5.981***	211.1***	386.8***		
	(0.000)	(0.000)	(0.000)	(0.000)		I(1)
CFBL	−16.80***	−12.31***	354.0***	844.0***		
	(0.000)	(0.000)	(0.000)	(0.000)	I(0)	
GRB	−7.575***	−4.255***	179.6***	253.8***		
	(0.000)	(0.000)	(0.000)	(0.000)	I(0)	
M2/GDP	−11.70***	−3.321***	168.7***	292.9***		
	(0.000)	(0.000)	(0.000)	(0.000)	I(0)	
EXR	−7.729***	−2.698***	161.2***	183.1***		
	(0.000)	(0.004)	(0.001)	(0.000)	I(0)	

Source: Researcher's Conception. ***, ** and * represent 1%, 5% and 10% level of significance, probability values in brackets.

In Table 4, the panel unit root tests, such as Levine et al. (2002), Im et al. (2003), Fisher-ADF, and Fisher-PP tests (Madala and Wu, 1999), are used to ascertain the unit root in the series and the stationarity levels of the variables. The results show a unit root in the variables as the probability figures of the variables are less than 0.05. Thus, the null hypothesis of no unit root in the variables is rejected. Some variables are integrated at level, while others are integrated at first difference, validating the suitability of the ARDL analysis.

From Table 5, the Pedroni and Kao cointegration tests are employed. The Pedroni cointegration shows that cointegration exists between green finance and financial efficiency in the countries since at least 6 out of 7 tests have probability values less than 0.05. The Kao cointegration test revealed that cointegration exists between green finance and financial efficiency in the states since the probability values of the models are less than 0.05. Additionally, the ADF-statistics for Pedroni and Kao cointegration tests confirm that cointegration exists.

Table 5. Cointegration test.

	Pedroni Cointegration							Kao Cointegration
	Within-Dimension				Between-Dimension			ADF-Statistic
	Panel V-Statistic	Panel rho-Statistic	Panel PP-Statistic	Panel ADF-Statistic	Group rho-Statistic	Group PP-Statistic	Group ADF-Statistic	
Model 1	−3.060 (0.998)	8.840*** (0.000)	6.388*** (0.000)	6.011*** (0.000)	10.36*** (0.000)	−13.04*** (0.000)	5.174*** (0.000)	−9.168*** (0.000)
Model 2	−3.761 (0.139)	8.070*** (0.000)	5.668*** (0.000)	9.552*** (0.000)	11.17*** (0.000)	−2.392*** (0.008)	8.646*** (0.000)	−3.618*** (0.000)
Model 3	−3.905*** (0.000)	8.425*** (0.000)	6.773*** (0.000)	10.50*** (0.000)	10.78*** (0.000)	−7.842*** (0.000)	7.237*** (0.000)	−3.897*** (0.000)

Source: Researcher's Concept. ***, ** and * represent the 1%, 5% and 10% level of significance, probability values in brackets.

Table 6. ARDL long run analysis.

Variable	1	2	3
FMEI (−1)	0.014*	−0.060***	0.012**
	(0.076)	(0.000)	(0.040)
EPEXP	0.184**		
	(0.014)		
CFBL		−0.048***	
		(0.000)	
GRB			0.021***
			(0.000)
M2/GDP	0.249***	−0.021***	0.091***
	(0.000)	(0.001)	(0.022)
EXR	−0.012***	0.007	−0.599
	(0.000)	(0.458)	(0.686)
No. of Obs.	549	549	549
Hausman	2.454	116.3	109.3
	(0.874)	(0.000)	(0.000)
Normality	1.569	5.848	5.870
	(0.477)	(0.856)	(0.779)
Serial Corr.	0.601	1.119	0.085
	(0.876)	(0.859)	(0.154)
Ramsey	−0.081	−0.118	−0.759
	(0.687)	(0.369)	(0.369)
Heteroscedasticity	0.518	1.017	3.209
	(0.457)	(0.856)	(0.885)
R-square	0.691	0.804	0.720
	(0.072)	(0.051)	(0.049)

Source: Author's Concept. ***, ** and * represent 1%, 5%, and 10% significant levels, and (.) is the probability values.

The diagnostic tests validate the model employed. The normality tests p-values are 0.477, 0.856, and 0.779 respectively. This indicates that the residuals are habitually dispersed to ensure that the models' estimates are reliable. The absence of successive correlation in the model as shown by the p-values suggests that the models do not suffer from autocorrelation. The normality test results are insignificant. It means there is no strong evidence that the data is different from a normal distributive nature. The data is assumed to be normal. The Ramsey test results indicate that no functional form of misspecification exists. This implies that the model is correctly specified. Additionally, the heteroscedasticity test confirms the constant variance of residuals, which validates the reliability of the models. The Hausman test results are mixed, with the first model showing no endogeneity issues while models 2 and 3 reject the null hypothesis. This indicates that the fixed effects estimation is more appropriate for use. The goodness of fit values indicate that the exogenous variables greatly explained the endogenous variable.

In models 1 and 3, the current value of financial efficiency is positively influenced by its immediate past value. Financial efficiency tends to drift in the same direction over time. The positive lag suggests that high financial efficiency value in the past period pushes the current value of financial efficiency higher, showing a consistent increase in financial efficiency trend. In these models, the coefficients are closer to zero than to 1. This implies that adjustment back to equilibrium could be faster.

In models 2, the current value of financial efficiency reacts in the opposite direction to past values. This suggests that if the financial efficiency rises in one period, it is corrected by dropping in the subsequent period. The negative lagged coefficient of financial efficiency indicates its mean reversion from its original position. Any unusually high value is often followed by a drop to bring the value back to a long-term average point. This represents a balancing force that pulls financial efficiency back toward its equilibrium state.

The carbon footprint of bank loans negatively affects financial market efficiency in model 2. This reflects the detrimental impact of unmanageable banking services on financial stability. This is visible in some countries where heavy financing of carbon-intensive projects is raising concerns on green finance. The green bonds positively influence financial efficiency in model 3 demonstrating that sustainable financing mechanisms play a critical role in enhancing market performance. This is observable in countries with successful issuance of green bonds to provide resources for renewable energy projects. The findings corroborate with the outcomes of Paramati et al. (2020); Ngong et al. (2022a); Renzhi and Baek (2020) and disagree with the results of Maria et al. (2023); Ren et al. (2020).

The environmental protection expenditure has a positively significant effect on financial market efficiency in model 1 with a coefficient of 0.184. This means that an increase in environmental protection expenditure will affect financial market efficiency positively. Hence, high spending on environmental protection signals good sustainability practices, regulatory compliance, and long-term economic stability. The results agree with the findings of Ngong et al. (2022a), Paramati et al. (2020), and Renzhi and Baek (2020) and disagree with the results of Maria et al. (2023) and Ren et al. (2020).

This implies that firms and governments that invest in environmental protection often adopt better reporting and governance practices. Greater transparency reduces information asymmetry, allowing markets to allocate resources more efficiently. This increases investors' trust and improve the functioning of financial markets. The finding suggests that environmental responsibility and financial market development are complementary due to efficient market information flow. Increased environmental expenditure encourage green investments, environmental sustainability focused financing, and sustainable capital allocation which deepen and modernize financial markets. Environmental degradation creates economic uncertainty, regulatory penalties, and operational disruptions. Spending on environmental protection reduces the risks, thereby stabilizing markets and improving efficiency.

Financial deepening has a significant positive effect in models 1 and 3, stressing the significance of a well-developed financial sector in boosting market efficiency. This is evident in countries where financial inclusiveness strengthened market operations. Exchange rate variability negatively affects financial efficiency in models 1 and 3, underscoring the destabilizing effect of currency fluctuations. Persistent exchange rate instability exists in many countries which affects investors' confidence and market efficiency.

Table 7. ARDL short-run dynamics.

Variable	1	2	3
ECM (−1)	−0.761***	−0.511***	−0.768***
	(0.000)	(0.000)	(0.000)
ΔEPEXP	−0.201**		
	(0.096)		
ΔCFBL		0.043	
		(0.996)	
ΔGRB			−0.033
			(0.820)
ΔM2/GDP	−26.26	0.029	0.116
	(0.107)	(0.676)	(0.353)
ΔEXR	0.738	−0.106	0.307
	(0.586)	(0.539)	(0.190)

Source: Conceived by the Author. ***, ** and * represent 1%, 5%, and 10% significant levels, and (.) is the probability value.

The error correction term (ECM-1) is negative and statistically significant across all three models. This confirms a strong speed of change to long-run equilibrium. The coefficients indicate that about 76%, 51%, and 77% of any disequilibrium from the previous period is corrected in the current period. This suggests that the SSA financial markets respond relatively quickly to shocks. The coefficient for environmental protection expenses is negative and significant at the 10% in model 1. This indicates that a rise in environmental spending initially reduces financial market efficiency. This could be as a result of the high costs of regulatory compliance, which burdens financial institutions and divert resources from productive investments. Such trends are observed in countries where stern environmental conventions create short-term inefficiencies in financial markets as firms adjust to new compliance measures. Furthermore, the influence of the carbon footprint of bank loans and green bonds is statistically insignificant, suggesting that the indicators do not have an immediate effect on financial market efficiency. This is attributed to the slow integration of green financing in SSA, where green bond markets are still in the infancy stage. This highlights the necessity of long-term investments and policy consistency to fully realize the benefits of sustainable finance. The results agree with those of Paramati et al. (2020); Samour et al. (2019) and do not align with the results of Maria et al. (2023); Ren et al. (2020).

Financial deepening shows negative but insignificant effects in model 1 and positive but insignificant effects in models 2 and 3. This implies that the variations in financial depth do not substantially influence the financial market efficiency. Several countries experience fluctuations in financial deepening due to inconsistent credit availability, making its short-run impact unstable. The exchange rate does not show a significant effect on financial market efficiency. This could reflect the relatively weak transmission mechanisms between exchange rate movements and financial markets in SSA, where many economies still rely on external shocks and interventions to stabilize their currencies.

5. Conclusions and policy recommendations

Financial market efficiency is essential for growth and development globally. It enhances capital allocation, expands investment opportunities, and strengthens financial stability. Green finance is very vital in improving financial market efficiency since it encourages sustainable investments and mitigates environmental concerns. The findings indicate that environmental protection expenditure positively influences financial efficiency by enhancing market stability and investor confidence. The carbon footprint of bank loans has a negative effect, reflecting the financial risks associated with carbon-intensive lending. Green bonds' potential impact remains insignificant due to the underdeveloped state of the green finance market in SSA. Overall, the findings emphasize that sustainable finance and environmental responsibility integrate the policies that improve financial market efficiency.

The governments in SSA nations should enhance green finance initiatives by expanding the green bond market through tax incentives for sustainable investments and strengthening environmental sustainability goals regulations to encourage responsible financing. Financial institutions should be incentivized to reduce carbon footprint by shifting investments towards renewable energy. Regional economic blocs should develop harmonized regulations and investment frameworks to attract global green investments and enhance financial efficiency across the region. Firms and governments should invest in environmental protection by adopting better reporting and governance practices. Greater transparency reduces information asymmetry, allowing markets to allocate resources more efficiently. Governments should collaborate with private sector actors and finance institutions to scale up green finance.

Theoretically, this study explains how green finance forces firms to build internal green capabilities to satisfy external institutional pressures and market expectations. The conceptual variables' results are postulating that green finance is linear to financial efficiency contrary environmental Kunz curve. The impact of green finance on financial efficiency varies based on the level of regional economic development, governance, and policy uncertainty. Establish a theoretical link between institutional green finance like green bonds and operational efficiency. Show how sustainable funding channels like green loans lower the cost of capital and stimulate innovation, which drives financial efficiency. Constructed a localized financial efficiency Index using principal component analysis to measure the dependent variable. Employ the ARDL model to control for endogeneity when assessing the effect of green finance on financial competency. Future research is feasible on the link between artificial intelligence and financial market efficiency.

Author contributions

Chi Aloysius N: Methodology, editing, review, data.
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Use of AI tools declaration

During the preparation of this article, the authors used google to improve the readability, language editing, and formatting the outline. The authors reviewed, edited and paraphrased the content as necessary and take full responsibility for the accuracy, integrity, and originality of the published work.

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Data availability statement

The data used for this study is available upon request.

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