

Renewable Energy Investments and Sustainable Trade Development in Sub-Saharan Africa: The Role of Financial Development

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Abstract

The existing literature has largely overlooked the impact of renewable energy investments on sustainable trade development, particularly regarding consumption-based carbon emissions in Sub-Saharan Africa (SSA). Moreover, how financial development affects the nexus between renewable energy investment and sustainable trade development remains underexplored. This study addresses this gap by investigating the combined effects of financial development and renewable energy investments on sustainable trade development in SSA. Using panel data from 47 SSA countries over the period 2000–2022, the analysis employs the Panel Corrected Standard Errors (PCSE) estimation approach. The findings indicate that: (1) the direct effects of renewable energy investments promote sustainable trade development in SSA countries; (2) financial development promotes sustainable trade development in SSA countries; (3) financial development complements renewable energy investment promotes sustainable trade development in SSA; (4) the study reveals that the impact of renewable energy investments on sustainable trade development depends on the level of financial development above or below a specific threshold; (5) the study revealed that renewable energy investment and financial development have a predictive power of sustainable trade development in SSA countries.

1. Introduction

Environmental degradation is a significant global concern. This issue is primarily linked to the rising levels of carbon dioxide emissions (CO₂e), which have detrimental effects on the environment. The repercussions of increasing carbon emissions are alarming, impacting public health, the environment, and the economy. Existing literature suggests that environmental degradation, driven by CO₂ emissions, results from both economic and non-economic factors. While various economic indicators are recognized as determinants of environmental degradation, the literature underscores that international trade is the most critical factor in relation to CO₂ emissions (Abendin et al., 2024; Ma, Han, et al., 2022). International trade can affect CO₂ emissions in several ways. From a theoretical perspective, Heckscher-Ohlin theory posits that trade liberalization encourages specialization based on comparative advantage. Thus, if a country specializes in energy-intensive, carbon-intensive industries, trade increases emissions. Conversely, specialization in low-carbon or service sectors can reduce emissions. Under the Pollution Haven Hypothesis, trade relocates carbon-intensive production to countries with weaker environmental regulations, increasing CO₂ emissions and masking global environmental costs (Ma, Han, et al., 2022). Trade can increase carbon emissions by expanding production and energy demand. At the same time, it can reduce emissions by enabling cleaner and more efficient production technologies. This, therefore, suggests that the net environmental effect of trade depends on which of these forces dominates (Aawaar et al., 2024; Duodu et al., 2023). The interaction between renewable energy investment and financial development in shaping sustainable trade outcomes, as measured by consumption-based carbon emissions, represents a vital line of research for understanding how evolving global economic dynamics influence environmental sustainability. In this paper, sustainable trade development is conceptualized as the volume of carbon emissions associated with a given scale of trade activity and is proxied by consumption-based carbon emissions following Ma, Han, et al. (2022) and Aawaar and Abendin (2025). Accordingly, the two terms are treated as synonymous throughout this study.

In contrast, to counteract the negative impact of international trade on carbon emissions, this study emphasizes the importance of investing in renewable energy, particularly in environmentally friendly technologies. Such investments contribute to environmental sustainability by advancing knowledge and technology to promote greener production processes (Khan et al., 2020). Additionally, firms that invest in renewable energy technologies in response to stringent environmental policies produce goods that are both energy-efficient and environmentally friendly (Ma, Han, et al., 2022). Cleaner production practices foster economic growth and trade while ensuring a sustainable environment. Consequently, their role is crucial in influencing consumption-based carbon emissions and promoting sustainable trade development. For example, research conducted by Awaworyi Churchill et al. (2021) and Udeagha and Ngepah (2023) indicates that investments in low-carbon activities can increase consumption-based emissions. Conversely, these investments can also reduce such emissions. A country's commitment to developing solar, wind, hydroelectric, and geothermal power can significantly decrease reliance on fossil fuels for electricity generation (Abendin et al., 2024; Ma, Han, et al., 2022). The shift toward cleaner energy sources may reduce carbon emissions associated with energy production (Hasanov et al., 2021). Studies by Guo et al. (2022) and Zhang et al. (2023) further support the notion that investment in low-carbon initiatives can effectively help lower consumption-based emissions.

The role of financial development in advancing sustainable trade is crucial and cannot be overlooked. Financial development facilitates funding for low-carbon initiatives and encourages investment in efficient production methods and technologies, which can help reduce carbon emissions. For example, Aawaar et al. (2024) present evidence indicating that financial development positively influences sustainable trade in Africa. Similarly, Aawaar and Abendin (2025) demonstrate that financial development in African nations fosters sustainable trade progression. However, some scholars argue that financial development may also exacerbate environmental challenges by enabling individuals and businesses to access funds more easily. They suggested that financial support, particularly for firms that do not comply with environmental regulations, could lead to increased emissions. Thus, while the benefits of financial development are significant, its impact on a country's carbon emissions must also be carefully considered (Duodu et al., 2021; Ma, Han, et al., 2022; Nkaku et al., 2020). The above-mentioned literature suggests that the effects of renewable energy investment and financial development on carbon emissions are inconclusive. Moreover, the literature failed to examine the combined effects of renewable energy investment and financial development on sustainable trade development or consumption-based carbon emissions, particularly within the African context. Prior studies have primarily focused on the individual impacts of these factors, neglecting their synergistic effects on sustainable trade development. Furthermore, the role of financial development in the relationship between renewable energy investment and sustainable trade development remains underexplored.

In light of this context, this article seeks to explore the direct and indirect impacts of renewable energy investment and financial development on sustainable trade development, with a focus on consumption-based carbon emissions in Sub-Saharan African (SSA) countries. This study makes significant contributions to the existing literature on sustainable trade development. Notably, it addresses a gap in current research by investigating how renewable energy investment and financial development influence sustainable trade development, specifically in terms of carbon emissions derived from consumption. Previous studies have largely overlooked this important dimension (Duodu et al., 2023; Ma, Han, et al., 2022). Currently, there are limited studies examining

the direct and indirect effects of renewable energy investment and financial development on sustainable trade in Sub-Saharan African (SSA) countries. Furthermore, this study addresses a significant gap in the existing literature on Sustainable Development Goals (SDGs) by exploring the impact of financial market growth on consumption-based carbon dioxide emissions. Previous research has predominantly focused on carbon emissions arising from production, leaving this critical area largely overlooked. Additionally, this study enhances the measurement of renewable energy investment projects in Africa by applying principal component analysis (PCA).

2. Stylized facts on sustainable trade development, renewable energy investment, and financial development

Stylized facts serve as an essential empirical benchmark for contextualizing subsequent econometric analysis. In this regard, the study situates Sub-Saharan Africa's sustainable trade development, renewable energy investment, and financial development within a global comparative framework by examining mean annual consumption-based carbon emissions from 47 SSA countries over the period 2000–2022, alongside comparable data from the Americas (45 countries), Asia (46 countries), and Europe (26 countries). As illustrated in Fig. 1, emissions declined sharply across all regions in 2020 before rebounding in 2022, reflecting the contraction and subsequent recovery of global economic activity following the COVID-19 shock. The synchronicity of these trends underscores the global nature of health-induced economic disruptions and their uniform environmental implications.

Figure 2 compares renewable energy investment (REI) in sub-Saharan Africa (SSA) with three other regions using four indicators: IRHP, IWE, ISE, and IBE. Across all measures, SSA records substantially lower REI levels than Asia, the European Union, and the Americas. The figure also highlights a clear regional ranking, with Europe leading, followed by Asia, the Americas, and SSA, underscoring the persistent investment gap between Africa and other global regions.

The annual mean values of the financial development index for Sub-Saharan Africa (SSA) from 2006 to 2021, as shown in Fig. 3 alongside data from Asia, the European Union, and the Americas, reveal a general upward trend in financial development across all regions, though at distinctly different rates. Despite the global expansion of the financial sector during this period, SSA continues to lag behind other regions. This relatively weak performance is attributed to persistent structural and institutional constraints, including political instability, poor governance, and corruption, which hinder effective economic management and discourage foreign investment. Furthermore, insufficient infrastructure, particularly in transportation, energy, and communication, remains a significant barrier to financial deepening, economic activity, and trade integration both within the region and with external markets.

3. Literature Review and Hypothesis

3.1 Renewable energy investment and sustainable trade development

The connection between renewable energy investment and sustainable trade development remains relatively underexplored in the existing literature, especially when sustainable trade is framed in terms of consumption-based carbon emissions. Most studies tend to focus on pairwise relationships, such as the links between renewable energy and emissions or between trade and environmental quality, rather than incorporating renewable energy investment into a more comprehensive sustainable trade framework. This section aims to synthesize the literature by highlighting two prominent yet opposing strands and providing a critical explanation of the sources of their divergence.

The first strand of research indicates that investments in renewable energy and advancements in green innovation play a vital role in promoting environmental sustainability and, consequently, fostering sustainable trade development. From both production and consumption perspectives, such investments reduce the carbon intensity of goods that are consumed domestically and traded internationally, thereby lowering emissions associated with trade. Empirical evidence largely corroborates this mechanism. For instance, utilizing quantile ARDL methods, Udeagha and Ngepah (2022) demonstrate that investments in green technology decrease emissions throughout the distribution in South Africa, revealing heterogeneous yet consistently positive effects. Similarly, Guo et al. (2022) and Zhang et al. (2023) report that green investments and innovations in renewable energy in China contribute to reductions in carbon emissions and improvements in environmental quality. Studies by Liu et al. (2025) and Zhang et al. (2025) demonstrate that innovations in renewable energy significantly reduce global carbon emissions.

Within the nexus of trade and the environment, numerous studies indicate that enhancing trade-related infrastructure and facilitation, when paired with green investments, promotes sustainable trade outcomes. Iheonu et al. (2021) supported this notion by indicating that African countries' investment in green trade facilitation activities positively affects sustainable trade development in the region. Moreover, Abendin et al. (2024) also backed it by showing that improving seaport efficiency reduces consumption-based emissions in African countries, highlighting the significance of green logistics in fostering sustainable trade. Additionally, research by Duodu et al. (2023) shows that trade openness and facilitation can enhance environmental sustainability in Africa when supported by cleaner technologies. Evidence from Asia also supports the notion that investments in green energy contribute to improved environmental quality (Zhi-qiang et al., 2024). These results align with the Heckscher-Ohlin (H–O) trade theory and global value chain (GVC) theory, which suggest that when countries specialize based on their cleaner comparative advantages and engage in greener value chains, trade expansion can be achieved sustainably from an environmental perspective. Additionally, these findings illustrate the technique effect in the trade-environment literature, where cleaner technologies offset the scale effects associated with increased trade.

In contrast, another strand of literature suggests that energy-related investments may increase carbon emissions, seemingly contradicting the sustainability narrative. However, these findings can largely be attributed to factors such as investment composition, energy structure, and institutional context, rather than to renewable energy investments specifically. Udeagha and Ngepah (2023) demonstrate that public-private partnership (PPP) investments in South Africa are associated with higher CO₂ emissions, reflecting the predominance of fossil fuel-based energy projects. Similarly, Awaworyi Churchill et al. (2021) find that expanding transport infrastructure increases emissions, primarily due to scale effects and carbon-intensive construction processes. Raza et al. (2021)

demonstrate a nonlinear relationship between PPP energy investments and emissions in developing countries, illustrating that investments primarily in non-renewable energy contribute to environmental degradation. Similarly, Baajike et al. (2022) highlight comparable negative impacts in West Africa, linking these effects to inadequate environmental regulations and a limited adoption of green technologies.

The apparent contradictions in the literature arise not from renewable energy investments themselves, but rather from the authenticity of energy and trade-related investments as green, consumption-oriented, and supported by effective institutions. When investment focuses on renewable energy, green infrastructure, and efficient trade facilitation, it helps reduce emissions associated with consumption and trade. In contrast, investments in fossil fuels or carbon-intensive infrastructure increase emissions, even as investment levels rise. Based on this synthesized evidence, we hypothesized that:

H₁

Renewable energy investments have a non-linear effect on sustainable trade development in sub-Saharan Africa.

3.2. Financial development and sustainable trade development

The relationship between financial development and sustainable trade has largely been analyzed through the perspective of carbon emissions, with few studies explicitly focusing on sustainability-adjusted trade outcomes. Current research highlights a complex and non-linear connection, showcasing the competing theoretical frameworks through which financial development affects the environmental performance associated with trade.

On one hand, financial development can significantly enhance sustainable trade growth by improving access to credit, facilitating capital mobility, and enabling investment in cleaner technologies and energy-efficient production processes. Well-functioning financial systems alleviate capital constraints faced by firms, empowering them to adopt low-carbon technologies, comply with environmental regulations, and transition towards cleaner export structures. Empirical evidence supports this relationship; for instance, Musah et al. (2022) demonstrate that capital mobility improves environmental quality and reduces trade-adjusted carbon emissions in Africa, indicating that financial openness can foster greener trade patterns. Another study focused on Sub-Saharan African countries indicates that financial development plays a significant role in promoting sustainable trade development. This finding aligns with the broader literature, which considers financial development as a key catalyst for integrating economic growth, trade expansion, and environmental sustainability in developing regions (Abendin et al., 2024). Aluko and Obalade (2020) demonstrate, through the STIRPAT framework, that the development of financial systems plays a significant role in promoting environmental sustainability in African economies. Evidence from China further supports this notion, indicating that financial inclusion helps reduce trade-adjusted carbon emissions by fostering more efficient and cleaner production methods (Ma, Khan, et al., 2022). These findings resonate with the scale–technique trade-off inherent in the Environmental Kuznets Curve (EKC) hypothesis, as noted by Mahmood (2020), which suggests that while financial development may initially increase emissions, it ultimately contributes to cleaner outcomes as economies evolve.

In contrast, the literature offers an alternative perspective that highlights the emissions-increasing effects of financial development, particularly in contexts marked by weak environmental regulations and carbon-intensive trade practices. Increased access to finance may encourage industrial growth, intensify competition for resources, and increase production for export markets, which can lead to higher emissions. This effect is particularly evident when financial resources are allocated to pollution-intensive sectors or when foreign direct investment (FDI) capitalizes on regulatory weaknesses. Ma, Han et al. (2022) shows that financial deepening can exacerbate environmental outcomes when investments are directed to companies that do not comply with regulatory standards. Supporting this perspective, Sattar et al. (2022) found that Chinese foreign direct investment (FDI) has increased carbon emissions in South Asian economies. Similarly, Duodu et al. (2021) observe that FDI leads to short-term emissions growth in Africa, consistent with the pollution haven hypothesis (PHH). Further studies concentrating on sub-Saharan Africa bolster this viewpoint, as Nkalu et al. (2020) and Habiba and Xinbang (2022) document a non-linear relationship between financial development and CO₂ emissions.

The existing literature indicates that the influence of financial development on sustainable trade growth is inherently conditional, reliant on factors such as institutional quality, environmental regulation, trade composition, and the direction of capital flows. The simultaneous presence of both emission-reducing and emission-increasing effects highlights the tension between technology-enhancing and scale-expanding mechanisms. This complexity underscores the need to frame sustainable trade development in terms of consumption- or trade-adjusted emission metrics and to conduct empirical assessments to determine the circumstances under which financial development fosters or hinders environmental sustainability in trade.

Building on this mixed theoretical and empirical foundation, this study proposes the following hypothesis:

H₂

Financial development has a non-linear and context-dependent effect on sustainable trade development.

3.3 Financial development and renewable energy investment

The literature exploring the connection between financial development and renewable energy investment, although still somewhat limited, reveals a complex and context-dependent relationship rather than a consistently positive effect. Generally, financial development is anticipated to enhance renewable energy investment by improving access to credit, lowering financing costs, and facilitating risk-sharing for capital-intensive green projects. However, empirical evidence indicates that these mechanisms function unevenly across different countries and levels of financial deepening.

Numerous studies indicate a positive correlation between financial development and the deployment of renewable energy, particularly in developing economies where financing constraints are significant. For example, Ndubuisi et al. (2023) demonstrate that in sub-Saharan Africa, financial development boosts renewable energy consumption, underscoring the importance of financial intermediation in channeling resources toward cleaner energy technologies.

Prempeh (2023) demonstrates that financial development plays a crucial role in stimulating renewable energy investment in Ghana, highlighting the significance of domestic financial systems in facilitating green energy transitions within low-income contexts. However, more recent studies urge caution against assuming a straightforward linear relationship. Dogan and Afsar (2023) in their examination of E-7 economies, identify a nonlinear and threshold-dependent impact of financial development on renewable energy investment. Their research indicates that while early stages of financial development can enhance renewable energy investment, excessive or inefficient deepening of financial resources may undermine this positive effect, thus supporting the Pollution Haven Hypothesis (PHH) view. This attenuation can be attributed to the misallocation of financial resources toward carbon-intensive sectors when financial markets expand without sufficient green-oriented regulation. This evidence sheds light on why financial development does not always lead to sustained growth in renewable energy investments (Aawaar et al., 2024). Green finance directs investment towards low-carbon products and services for both households and businesses, utilizing instruments such as green loans and bonds. These financial tools enhance the affordability of energy-efficient appliances, electric vehicles, and sustainable housing, ultimately reducing the carbon intensity of consumption. Alharbi et al. (2023) support this idea by highlighting that green finance fosters renewable energy investment worldwide.

This perspective is further supported by studies that underscore the structure and orientation of financial systems. Horky and Fidrmuc (2024) contend that conventional financial institutions often prioritize established, carbon-intensive industries due to their lower perceived risks and greater short-term returns, consequently crowding out renewable energy initiatives. In contrast, advanced and well-regulated financial markets in advanced economies are more effective at directing funds toward green energy through targeted instruments, regulatory support, and financial innovation. This indicates that the quality of financial development, rather than its sheer size, is crucial for financing renewable energy (Nyeadi, 2023).

Evidence from emerging economies underscores these complexities. Athari (2024) analyzes data from BRICS countries and concludes that financial stability and economic openness positively affect renewable energy investment, whereas economic growth appears to negatively influence it. This latter finding indicates that growth in these economies may still rely on fossil fuel-based industrialization, thereby diverting financial resources from renewable energy initiatives. The study underscores the complementary nature of technological progress and financial innovation, highlighting that financial development alone is inadequate without supportive institutional and technological frameworks. Overall, the existing literature suggests that financial development can serve both as a catalyst and a constraint for renewable energy investment. Positive impacts are more likely to prevail in financially constrained economies or in those with robust green finance frameworks in place. In contrast, negative or diminishing effects tend to arise in financial systems that favor carbon-intensive activities or experience inefficient resource allocation. These mixed findings underscore the necessity for empirical analysis that explicitly considers nonlinearities, institutional quality, and the interplay between financial development and broader economic structures. Accordingly, we propose the following hypothesis:

H3

Renewable energy investments have a conditional effect on sustainable trade development in sub-Saharan Africa, shaped by financial development.

3.4. Literature gap

The reviewed literature above presents conflicting evidence regarding the effects of renewable energy investments on environmental sustainability. Most studies have focused on the relationship between renewable energy investment and environmental quality or CO₂ emissions without explicitly addressing its effects on sustainable trade development or consumption-based carbon emissions, particularly in the African context (Aluko & Obalade, 2020; Musah et al., 2022). More importantly, no study in the analysis examines how financial development affects the link between investments in renewable energy in Africa and other areas. Our research examines how Africa's financial development affects the impact of investments in renewable energy on sustainable trade development, thereby addressing the literature gaps.

4. Theoretical framework and empirical model specifications

4.1. Theoretical framework

Sustainable trade development encompasses not only the growth of trade volumes but also enhancements in environmental quality, emissions efficiency, and the long-term competitiveness of traded goods. This study synthesizes theories from trade, energy, and finance, supported by empirical evidence, to examine how investments in renewable energy and financial development affect sustainable trade in BRICS economies. From the perspective of comparative advantage, the key determinants of trade patterns include production costs, factor endowments, and technological capabilities (Ricardo, 1817). According to the theory of comparative advantage, reliance on fossil fuels can be reduced through investments in renewable energy, thereby fostering a comparative advantage in environmentally friendly goods. Empirical studies provide strong support for this theory. For example, the studies by Guo et al. (2022) and Zhang et al. (2023) have suggested that investment in renewable energy fosters sustainable trade development. However, the results of Raza et al. (2021) and Baajike et al. (2022) contradict this view by indicating a negative relationship between renewable energy investment and carbon emissions. The Pollution Haven Hypothesis (PHH) asserts that environmental regulation and energy structure are crucial for achieving sustainable trade (Copeland & Taylor, 2004). This theory suggests that in the absence of clean energy and adequate financing, countries may concentrate on pollution-intensive exports. By reducing emissions intensity, renewable energy investment allows firms to transition away from polluting technologies, thereby mitigating the effects of the PHH and enhancing the environmental sustainability of exports. Numerous empirical studies have supported the PHH theory. Research by Abendin et al. (2024) has highlighted the positive impact of financial development on sustainable trade development. Furthermore, the findings of Aawaar et al. (2024) demonstrate that financial development enhances sustainable trade development in Sub-Saharan African (SSA) countries. Conversely, Aawaar and Abendin (2025) identified a nonlinear relationship between financial development and sustainable development in African nations. Overall, these theories and empirical

results suggest a cohesive pathway in which investments in renewable energy and financial development contribute to structural competitiveness, capital mobilization, technological advancement, and emissions reduction, ultimately advancing sustainable trade development.

4.2 Empirical model specifications

Based on the above theoretical rationale, we developed the following empirical model (Eq. (2)) to analyze the effects of renewable energy investment and financial development on sustainable trade development in sub-Saharan African countries.

$$SUSTD_{it} = f(REI_{it}, FD_{it}) \quad 1$$

Where $SUSTD_{it}$ represents sustainable trade development country i at time t . REI_{it} denotes renewable energy investment in country i at time t , while FD_{it} denotes financial development in country i at time t .

$$\ln SUSTD_{it} = \alpha_0 + \beta_1 \ln REI_{it} + \beta_2 \ln FD_{it} + \beta_3 \ln POP_{it} + \beta_4 \ln ECO_{it} + \beta_5 \ln GDP_{it} + \beta_6 \ln IMP_{it} + \beta_7 \ln EXP_{it} + \beta_8 \ln INTRATE_{it} \quad 2$$

Equation 2 can be reformulated to incorporate the interaction between renewable energy investment and financial development, as demonstrated in Eq. (3).

$$\ln SUSTD_{it} = \alpha_0 + \beta_1 \ln REI_{it} + \beta_2 \ln FD_{it} + \beta_3 (\ln REI_{it} * \ln FD_{it}) + \beta_4 \ln POP_{it} + \beta_5 \ln ECO_{it} + \beta_6 \ln GDP_{it} + \beta_7 \ln IMP_{it} + \beta_8 \ln INTRATE_{it} \quad 3$$

4.3 Econometric estimation methods

This study conducted preliminary examinations, including cross-sectional dependence, unit root, and cointegration, as outlined by Pesaran (2007), to avoid erroneous estimations. Cross-sectional dependence represents a critical issue in the econometric analysis of panel data, attributable to the increasing interconnectivity of economies. The impact of a sudden change in one country's economic policy can have substantial consequences for other nations. The Cross-Sectional Dependency Test (CSD) developed by Pesaran (2004) is employed to examine this. Following the confirmation of cross-sectional dependency in the series, the study utilized second-generation unit root tests to assess the stationarity properties of the series. Second-generation unit root tests were employed due to their ability to address econometric issues related to cross-sectional dependence. The study employed the Pesaran (2004) cross-sectional augmented Dickey-Fuller (CADF) method, which addresses the shortcomings of the original model by including unobserved components. Eq. (9) represents the estimation of the CADF statistic in regression. The Westerlund (2007) second-generation cointegration test is appropriate for identifying long-term connections between variables in this study. Compared to first-generation tests, it provides a more effective solution for addressing endogeneity and common driver (CD) concerns. The test presents four test statistics, including two statistics for group means and panel means, and assumes a null hypothesis of no long-term correlation.

This study employed panel corrected standard errors (PCSE) as its baseline estimation method due to several advantages over alternative techniques like Driscoll-Kraay and GMM. The panel data exhibited characteristics such as cross-sectional dependency, heteroskedasticity, and contemporaneous correlation among nations, with a larger temporal dimension ($T > N$) relative to the cross-sectional dimension. Given these conditions, PCSE provides consistent and efficient inference by directly modeling the variance-covariance structure of the errors, as opposed to depending on nonparametric adjustments, which is a notable improvement over the Driscoll-Kraay method (Hoechle, 2007). Driscoll-Kraay standard errors are designed for large N panels but may yield biased outcomes with moderate T due to their dependence on asymptotic properties and insufficient accounting for contemporaneous correlations arising from global shocks, especially pertinent in energy markets and international trade integration. Generalised Method of Moments (GMM) estimators are employed to analyse dynamic panels characterized by large N and small T , addressing endogeneity and dynamic bias; nonetheless, they encounter difficulties such as instrument proliferation and weak identification, while failing to account for cross-sectional dependence affected by global factors. In this context, Panel-Corrected Standard Errors (PCSE) represent the optimal approach, harmonizing flexibility with dependable inference corresponding to the panel structure.

This study utilized the novel second-stage instrumental variable (2SIV-DPD) technique and the enhanced panel Granger causality test developed by Xiao et al. (2023) as a robustness check to the PCSE estimations. In the presence of cross-sectional dependence and potential endogeneity, the two-stage instrumental variable defactored panel data (2SIV-DPD) estimator is used as a robustness check to the PCSE results, as it is better suited to this setting than conventional GMM approaches. Instrument validity within the 2SIV-DPD framework is not evaluated solely through post-estimation overidentification tests. Rather, the estimator applies a defactored two-stage IV procedure that removes unobserved common factors from both the endogenous regressors and the instrument set, thereby reducing potential violations of the exclusion restriction caused by pervasive global shocks and cross-sectional dependence. As a result, instrument admissibility is embedded in the identification strategy, with the Hansen J-test serving as a confirmatory diagnostic rather than the primary basis for identification (Kripfganz & Sarafidis, 2021). We employed the lagged values of the endogenous variables (POP, GDP, FD, ECO, IMP, EXP, REI, and INTRATE) as instruments. This is based on the view that economic variables such as those in this study exhibit persistence over time. This persistence ensures a strong correlation between lagged and current values, satisfying instrument relevance.

4.4 Data and measurement

This study employed panel data from 47 African countries to assess the dependent variable, as all indicators were accessible in these countries. The study covered the period from 2000–2022. The dependent variable of this study is sustainable trade development (SUSTD). We measured sustainable trade by utilizing consumption-based carbon emissions data from the Global Carbon Atlas (2023) as follows:

$$SUSTD_{it} = \ln \left(\frac{CBE_{it}}{GDP_{it}} \right) \quad 4$$

Where $SUSTD_{it}$ denotes the sustainable trade development of country i at time t . CBE_{it} represents the country i 's consumption-based emissions at time t , while GDP_{it} represents country i 's gross domestic product at time t . Consumption-based carbon emissions account for the total environmental impact of domestic consumption, encompassing the emissions embedded in trade. This approach effectively illustrates the true ecological footprint of trade activities. The methodology is fundamentally grounded in the Heckscher-Ohlin theory, which links a nation's factor endowments and trade specialization to the environmental intensity of its production and consumption patterns. Empirical studies, including Ma, Han et al. (2022), Abendin et al. (2024), Aawaar et al. (2024), and Aawaar and Abendin (2025) used a similar measure of sustainable trade development. The main independent variables in this study are renewable energy investment (REI) and financial development (FDI). The REI index is measured based on four indicators of renewable energy investment activities: investment in renewable hydropower (IRHP), investment in wind energy (IWE), investment in solar energy (ISE), and investment in bioenergy (IBE). Earlier studies, such as Yang et al. (2022) and Kartal et al. (2023), used similar indicators to measure renewable energy investment. The study used principal component analysis (PCA) to construct the REI index. We employed the following formula to normalize the REI index from the PCA technique (Abendin & Pingfang, 2022).

$$F_{it} = [F_{it} - \min (F_{it})] / [\max F_{it} - \min (F_{it})] \times 5$$

Where F_{it} denotes the level of renewable energy investments of country i in year t .

The REI results from the principal component analysis are reported in Table 1. The table displays the significant loadings of all the factors utilized in calculating the renewable energy investment. This indicates that all of the series satisfied the criteria for inclusion in the computation of the indexes. All indicators used to compute the Renewable Energy Investment (REI) Index were obtained from the International Renewable Energy Agency (IRENA) database. As previously stated, these factors were selected based on the literature. Table 2 provides a succinct overview of each variable, facilitating the comprehension and clarity of the empirical investigation.

Table 1
Principal component analysis of renewable energy investment index results

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	1.526	0.522	0.382	0.382
Comp2	1.004	0.068	0.251	0.633
Comp3	0.937	0.403	0.234	0.867
Comp4	0.533	-	0.133	1.000
Eigenvectors Variables		Comp1	Comp2	
Renewable hydropower investment (IRHP)		0.650*	0.188	
Wind energy investment (IWE)		0.677*	0.013	
Solar energy investment (ISE)		0.334*	-0.139	
Bioenergy investment (IBE)		-0.087	0.972**	

*Significant loadings under component 1. **Denotes significant loadings under component 2.

Table 2
Variable definition

Variable	Definition	Measurement	Data Source
SUSTD	Sustainable trade	As per Eq. (1)	Global Carbon Atlas
REI	Renewable energy investment	As per Eq. (2)	IRENA
POP	Population growth	Annual population growth	WDI
FD	Financial development	Financial development index	IMF
GDP	Economic activity	GDP per capita	WDI
ECO	Economic innovation	Environment-related technologies as % of all technologies.	WDI
IMP	Imports	Total imports as a % of GDP	WDI
EXP	Exports	Total exports as a % of GDP	WDI
INTRATE	Interest rates	Real interest rate	WDI

5. Empirical results and discussion

5.1 Preliminary Estimations

5.1.1 Descriptive Statistics

The descriptive statistics for the variable utilized in this investigation are shown in Table 3 below. Table 3 shows that investment in wind energy (IWE) is associated with the highest average value, while the interest rate (INTRATE) is associated with the lowest average value. Table 3 further demonstrates that most variables, except SUSTD and INTERATE, exhibit reasonably high dispersion around their mean values, as indicated by the standard deviation, which is considerably larger than the mean.

Table 3
Descriptive Statistics Results

Variable	Obs	Mean	Std. dev.	Min	Max
SUSTD	1081	0.842	0.642	-3.045	2.747
IRHP	1081	1922.582	557.481	636.648	3579.250
IWE	1081	4778.823	5036.453	391.000	30703.300
ISE	1081	7.993	1.002	5.969	10.332
IBE	1081	4.752	0.379	3.920	5.899
FD	1081	0.769	0.223	0.255	1.432
POP	1081	0.194	0.043	0.017	0.393
ECO	1081	1.811	1.256	2.240	2.868
GDP	1081	12.260	1.013	10.172	14.510
IMP	1081	11.047	3.039	4.701	21.165
EXP	1081	0.802	0.213	0.035	1.742
INTRATE	1081	0.070	0.066	0.378	0.616

5.1.2 Cross-sectional dependency, unit root, and cointegration test

This section of the study first considered the cross-sectional dependency among the variables. Table 4 documents the cross-sectional dependency test results for variables including SUSTD, REI, FD, POP, ECO, GDP, IMP, EXP, and INTRATE. The null hypothesis that African countries do not depend on each other across periods is rejected at significance levels of 1%, 5%, and 10% for the FD, POP, GDP, ECO, and IMP variables, respectively. This indicates mutual interdependence and spillover effects among SSA countries in these variables, implying that economic or policy shocks in one country could influence others. To account for this dependence, the Cross-Sectionally Augmented Dickey-Fuller (CADF) test was employed to check for unit roots while controlling for cross-sectional dependence. The results of the CADF test are shown in Table 5. We permitted a trend in the unit root test of the series' characteristics. According to the findings, each variable is integrated in order I (1). This suggests that an econometric estimate using the study's series would not provide erroneous findings. In addition, the study used the Westerlund (2007) cointegration test to investigate the possibility of a long-term correlation between the series included in our model. Table 6 presents the results of the cointegration test conducted by Westerlund (2007). Panel and group statistical analysis is used to verify the findings. The long-term link between the variables is shown in Table 6.

Table 4
Cross-sectional dependency results

Variable	CD-test	p-value	mean abs(ρ)
SUSTD	-1.484	0.138	0.330
REI	-0.492	0.623	0.190
FD	-2.533**	0.011	0.430
POP	-1.908*	0.056	0.210
ECO	2.550**	0.011	0.555
GDP	3.379***	0.001	0.550
IMP	4.193***	0.000	0.400
EXP	1.493	0.135	0.360
INTRATE	-1.511	0.131	0.300
Note: Under the null hypothesis of cross-section independence, $CD \sim N(0,1)$ P-values close to zero indicate data are correlated across panel groups. Note: ***, **, and * are for 1%, 5%, and 10% significance level.			

Table 5
Panel unit root test results

Variable	Trend and Intercept	
	Level	1st Difference
SUSTD	-1.908	-3.213***
REI	-2.732***	-
FD	-2.033	-3.426***
POP	-2.370***	-
ECO	-1.395	-2.627***
GDP	-1.851	-2.962***
IMP	-1.524	-3.330***
EXP	-1.884	-3.445***
INTRATE	-2.128*	-
Note: ***, **, and * are for 1%, 5%, and 10% significance level. Critical values: 1%=-2.230; 5%=-2.110; and 10%=-2.040.		

Table 6
Cointegration test results

Statistic	Value	Z-value	P-value	Robust P-value
Gt	-2.348	-4.279***	0.000	0.000
Ga	-8.619	-1.793***	0.037	0.000
Pt	-13.052	-2.905***	0.002	0.000
Pa	-5.979	-2.425***	0.008	0.000
Note: ***, **, and * are for 1%, 5%, and 10% significance level.				

5.2 Empirical Results

5.2.1 Results of PCSE estimations

Table 7 presents the direct and interactive impacts of renewable energy investments (REI, IRHP, IWE, ISE, and IBE) and financial development (FD), while controlling for other explanatory factors. Model 1 documents the results of the total structure of renewable energy investment (REI) based on IRHP, IWE, ISE, and IBE, while models 2–5 report the results of the individual sub-indicators; IRHP, IWE, ISE, and IBE, respectively, as shown in Table 7. Table 7 shows that population growth (POP) in SSA countries positively impacts consumption-based emissions in all the models, indicating that population growth significantly worsens sustainable trade development, lending credence to the findings of (Yang et al., 2022). Furthermore, the coefficient on eco-innovation (ECO) for consumption-based emissions is negative and statistically significant across all five models, indicating that increased eco-innovation promotes sustainable trade development in SSA countries. Our findings contradict Abendin et al. (2024) but support those of Ma, Han, et al. (2022). Regarding economic growth (GDP), the coefficients are positive and significant in all five models, which means economic growth increases consumption-based emissions (Yang et al., 2022) hence worsening sustainable trade development in SSA countries.

Similarly, the coefficients for imports (IMP) in all five models indicate a positive, statistically significant impact on consumption-based emissions. This implies that increased imports from SSA countries increase consumption-based emissions, worsening sustainable trade development in the region (Ma, Han, et al., 2022). Conversely, Table 7 shows that exports (EXP) and interest rates (INTRATE) negatively affect consumption-based carbon emissions. However, the INTRATE coefficients are statistically insignificant across all five models, as shown in Table 7. This means that SSA exports can reduce consumption-based emissions (Abendin et al., 2024; Ma, Han, et al., 2022), therefore fostering sustainable trade development in the region. These results further imply that if SSA nations increase the efficiency of their exports, which they utilize in their manufacturing processes, consumption-based carbon emissions will decrease.

Regarding financial development (FD), Table 7 shows that FD decreases consumption-based carbon emissions across all models, thereby promoting sustainable trade development and supporting **Hypothesis 2**. The results suggest that increased financial development has mitigated carbon emissions from consumption in sub-Saharan African nations. The results suggest that implementing financial development strategies may reduce carbon emissions associated with consumption. Financial development contributes to reducing carbon emissions by supporting climate finance initiatives. These initiatives help mobilize resources for mitigation and adaptation projects, particularly vital in developing countries. As a result, countries can shift towards renewable energy economies and decrease the intensity of emissions in their production processes. Further, financial development helps allocate resources to renewable energy investment and to the development of environmentally sustainable trade-enabling infrastructure, such as green ports, public transportation systems, and green buildings (Ma, Han, et al., 2022). These investments can reduce carbon emissions from buildings and transportation, which are significant sources in many economies. This outcome aligns with the findings of Aluko and Obalade (2020), who showed that financial development reduces carbon emissions in Africa.

As evident in Table 7, Model 1, the estimated coefficients from the PCSE technique indicate that REI has a negative impact on consumption-based carbon emissions, consistent with **Hypothesis 1**. This indicates that an increase in renewable energy investment reduces consumption-based emissions by 0.069 at 1% significance level. An economic implication of this finding is that investment in renewable energy can reduce consumption-based carbon emissions, thereby promoting sustainable trade development in SSA countries. This discovery indicates that economic policies aimed at promoting investment in renewable energy can effectively lower consumption-based emissions. This effect may stem from the energy-efficiency improvements and technological advancements that accompany such investments. The large-scale deployment of renewable energy strengthens infrastructure, smart grid systems, and cleaner production technologies, ultimately resulting in reduced energy consumption and diminished emissions in final consumption. Another potential explanation for this finding is that investment in renewable energy transforms trade patterns by encouraging the adoption of greener goods and inputs. Countries that increasingly depend on renewable energy are diminishing their reliance on carbon-intensive imports, such as fossil fuels and energy-intensive raw materials, while sourcing or producing cleaner alternatives instead. This shift results in a decrease in the carbon content of imported goods. Our findings are consistent with Udeagha and Ngepah (2022), who indicated that investments in renewable energy are crucial for mitigating carbon emissions in South Africa. However, our findings contradict those of Awaworyi Churchill et al. (2021) that investment activities in renewable energy may lead to an increase in carbon emissions due to increased consumption in Africa.

Model 1 in Table 7 also reports the results for the interaction term between REI and financial development (FD). The coefficients indicate a negative effect on consumption-based carbon emissions, which aligns with **Hypothesis 3**. Thus, the joint impact of renewable energy investment and financial development fosters sustainable trade development. This indicates that financial development plays a crucial role in enhancing the environmental effectiveness of renewable energy investments. Policymakers should integrate renewable energy policies with financial sector reforms to boost clean energy investments and improve financial markets. This integrated approach is likely to yield more effective emissions reductions compared to addressing these issues separately.

As shown in Table 7, renewable energy investment (REI), proxied by hydropower investment (IRHP), has a negative and statistically significant effect on consumption-based carbon emissions at the 10% significance level. The coefficient indicates that an increase in hydropower would reduce consumption-based carbon emissions by approximately 0.138, thereby promoting sustainable trade development in SSA. This outcome can be explained by several mechanisms. One possible explanation is that lower electricity costs from hydropower expansion may induce a rebound effect, leading to lower overall energy use and production in trade-related sectors. These findings suggest that renewable energy investment, combined with complementary policies such as carbon pricing and energy-efficiency measures, can reduce consumption-based emissions. This finding is consistent with those of Udeagha and Ngepah (2022), while in contrast with those of Razzaq et al. (2023), who provide evidence that investing in renewable energy increases carbon dioxide emissions.

Moreover, Model 2 in Table 7 indicates that the interaction between financial development (FD) and investment in renewable hydropower (IRHP) has a negative, statistically significant effect on consumption-based carbon emissions, underscoring the complementarity between finance and clean energy investment. The estimated coefficient suggests that a consistent increase in investment in hydropower and financial development reduces consumption-based emissions by approximately 0.010. This outcome indicates that financial development enhances the efficacy of hydropower investment by easing credit limitations, reducing financing costs, and optimizing capital allocation for large-scale, capital-intensive renewable projects. Without efficient financial mechanisms, investments in hydropower may be delayed, lead to cost overruns, or be restricted in integration into production networks. Improved financial intermediation thus promotes the use of hydropower as a dependable, low-carbon energy source, reducing the carbon intensity of energy inputs in traded products and, in turn, consumption-based emissions.

Moreover, Table 7 demonstrates that investment in wind energy (IWE) in model 3 is an additional renewable energy investment avenue, with a negative and substantial direct effect, thereby confirming **Hypothesis 1**. This finding suggests that investments in wind energy have a distinct impact on carbon emissions depending on consumption in the nations under consideration in Sub-Saharan Africa. The conclusion of this study is that wind energy significantly reduces emissions resulting from consumption, therefore fostering the growth of sustainable trade. Wind energy can reduce consumption-based carbon emissions by replacing fossil fuels, such as coal, oil, and natural gas, which are major sources of elevated emissions. This finding is consistent with the conclusions of Yang et al. (2022) and He et al. (2023) who demonstrated that investing in wind energy reduces carbon dioxide emissions. The results indicate that the interaction effect of financial development (FD) and investment in wind energy (IWE) significantly influences the consumption-based carbon emissions equation at the 1% level, with a negative coefficient. The estimated coefficient indicates that a consistent increase in both FD and IWE reduces consumption-based emissions by approximately 0.185, thereby fostering sustainable trade development in sub-Saharan Africa (SSA). The combined effects of FD and IWE hold promise for promoting sustainable trade initiatives. This outcome implies that well-developed financial markets, coupled with investments in wind energy, can effectively advance sustainable trade development in SSA countries. This finding further validates hypothesis 3.

Table 7
The panel corrected standard errors (PCSE) estimation results.

Variable	REI	IRHP	IWE	ISE	IBE
	M1	M2	M3	M4	M5
POP	0.086*** (0.001)	0.087*** (0.001)	0.087*** (0.001)	0.087*** (0.001)	0.087*** (0.001)
ECO	-0.031*** (0.007)	-0.029*** (0.070)	-0.020** (0.010)	-0.326*** (0.110)	-0.027*** (0.007)
GDP	0.024** (0.009)	0.020** (0.009)	0.012* (0.010)	0.016* (0.009)	0.135*** (0.029)
IMP	0.047*** (0.003)	0.047*** (0.003)	0.047*** (0.003)	0.047*** (0.003)	0.054*** (0.003)
EXP	-0.059*** (0.026)	-0.057** (0.026)	-0.063** (0.026)	-0.044* (0.025)	-0.049* (0.025)
INTRATE	-0.080 (0.064)	-0.069 (0.064)	-0.075 (0.064)	-0.101 (0.065)	-0.087 (0.060)
FD	-0.039*** (0.072)	-0.144*** (0.048)	-0.016 (0.066)	-0.135*** (0.047)	1.704*** (0.432)
REI	-0.069*** (0.031)				
REI*FD	-2.173*** (0.581)				
IRHP		-0.138* (0.072)			
IRHP*FD		-0.010* (0.001)			
IWE			-0.185*** (0.062)		
IWE*FD			-0.039*** (0.014)		
ISE				-0.357*** (0.108)	
ISE*FD				-0.110*** (0.033)	
IBE					-0.055** (0.027)
IBE*FD					-0.151*** (0.036)
Constant	-0.287* (0.157)	-0.291** (0.146)	0.183 (0.196)	2.994*** (0.884)	-1.635*** (0.370)
No. Obs.	1081	1081	1081	1081	1081
Year effect	Yes	Yes	Yes	Yes	Yes
R-squared	0.934	0.934	0.934	0.934	0.934
Note: ***, **, and * are for 1%, 5%, and 10% significance level. Standard errors in parentheses.					

Variable	REI	IRHP	IWE	ISE	IBE
	M1	M2	M3	M4	M5
Wald χ^2	5321.82	4828.71	17111.63	5079.66	4898.78
Note: ***, **, and * are for 1%, 5%, and 10% significance level. Standard errors in parentheses.					

The direct impact of investment in solar energy (ISE) is reported to be negative and statistically significant at the 1% level, as shown in Table 7 model 4. This suggests that investments in solar energy reduce consumption-based emissions in Sub-Saharan Africa by approximately 0.357. The findings underscore the need for targeted fiscal incentives to accelerate the adoption of solar energy. By implementing measures such as tax credits, import duty exemptions for solar technologies, feed-in tariffs, and concessional financing for solar projects, policymakers can enhance the role of solar energy in reducing emissions. Additionally, leveraging climate funds and hybrid financing approaches may attract private investment while mitigating project risks, given the financial constraints faced in Sub-Saharan Africa (SSA). This observation contradicts the conclusions of Baajike et al. (2022), who proposed that boosting solar panel manufacturing may lead to significant pollution. However, it is consistent with the results of Liu et al. (2025). Furthermore, we find a significantly negative interaction coefficient between ISE and FD. This finding suggests that investments in solar energy have a negative impact on consumption-based emissions in the presence of financial development, indicating potential improvements in sustainable trade development in SSA nations. As a result, FD and ISE interact well to reduce consumption-based emissions. In particular, a 0.110 decrease in consumption-based carbon emissions is linked to an increase in the degree to which FD complements ISE.

As shown in Table 7 for model 5, the direct effect of investment in bioenergy (IBE) is both negative and statistically significant at the 5% significance level. The coefficient indicates that an increase in IBE is associated with a reduction of approximately 0.055 in consumption-based emissions in Sub-Saharan African (SSA) nations, thereby fostering sustainable trade development in the region. This finding suggests that demand-side and lifecycle-based mitigation strategies should take precedence over production-side decarbonization efforts. To reduce reliance on carbon-intensive imported goods and fossil-fuel-based energy embedded in consumption, SSA policymakers should actively promote bioenergy throughout local value chains. The results align with the findings of He et al. (2023), validating **hypothesis 1**. Furthermore, as shown in Table 7, Model 5, the estimated coefficients reveal that the interaction effect between IBE and FD is both negative and statistically significant at the 1% level. This suggests that a consistent increase in the availability of bioenergy investment and efficient environmental funds from financial markets reduces consumption-based carbon emissions. The findings suggest that investments in bioenergy are more effective in reducing consumption-based carbon emissions when supported by a robust financial system. Policymakers should strengthen financial markets to channel capital into bioenergy-related initiatives, such as green bonds, sustainability-linked loans, bioenergy credits, and dedicated environmental investment funds. Moreover, establishing clear taxonomies and disclosure standards is essential to mitigate greenwashing and ensure that financial flows have a positive impact on bioenergy. This finding supports **hypothesis 3**.

5.2.2 Robustness checks (2SIV)

The PCSE specifications may be influenced by endogeneity. Potential concerns about endogeneity may arise from omitted-variable bias, in which relevant explanatory factors are inadequately represented in the model specification. Additionally, endogeneity may arise from simultaneity, leading to correlations between the explanatory variables and the disturbance term, or between the explanatory variables and unobserved country-specific characteristics. As a result, we employed the second-stage instrumental variable (2SIV) technique to address endogeneity concerns as a robustness check of the PCSE findings. This section will center on our primary variables of interest: renewable energy investment (REI) and financial development (FD). The 2SIV results are reported in Table 8. The findings indicate that an increase in renewable energy investment (REI) leads to a corresponding decrease in consumption-based carbon emissions or an increase in sustainable trade development level. Similarly, the 2SIV coefficients for financial development suggest that financial development decreases consumption-based carbon emissions, therefore promoting sustainable trade development. These findings are consistent with the PCSE results in Table 7, but differ in magnitude. Additionally, the joint effect of renewable energy investment (REI) and financial development (FD) on consumption-based carbon emissions is negative, as shown in Table 7, but differs in magnitude, indicating that it promotes sustainable trade development in SSA economies.

The 2SIV coefficients are larger than those derived from PCSE. The larger coefficients indicated by 2SIV suggest the presence of endogeneity-induced attenuation bias in the PCSE estimates. Although PCSE accounts for heteroskedasticity and correlation, it does not effectively address endogeneity, leading to biased estimates that tend to be reduced toward zero. In contrast, 2SIV removes the endogenous component using instruments, yielding estimates that more accurately reflect the causal effect and, thus, higher magnitudes than those from PCSE. These results imply that neglecting endogeneity may lead to an underestimation of the true magnitude, although the qualitative conclusion remains consistent. This is particularly relevant for policy interpretation, as the economic impact of the key variables may be greater than suggested by the baseline PCSE results.

Table 8
Robustness estimations with the second-stage instrumental variable (2SIV).

Variable	REI	IRHP	IWE	ISE	IBE
	M1	M2	M3	M4	M5
POP	0.082*** (0.002)	0.090*** (0.003)	0.088*** (0.001)	0.085*** (0.001)	0.092*** (0.001)
ECO	-0.021** (0.050)	-0.016 (0.056)	-0.113** (0.052)	0.019** (0.007)	-0.032*** (0.010)
GDP	0.452*** (0.045)	0.006 (0.039)	0.033*** (0.006)	0.020** (0.009)	0.685*** (0.111)
IMP	0.080*** (0.008)	0.049*** (0.005)	0.057*** (0.002)	0.051*** (0.002)	0.146*** (0.018)
EXP	0.108 (0.079)	-0.122** (0.052)	-0.208*** (0.039)	-0.179*** (0.047)	-0.318*** (0.104)
INTRATE	-2.869*** (0.237)	-0.158 (0.280)	-0.116*** (0.020)	-0.127*** (0.014)	-11.088*** (1.864)
FD	-0.666*** (0.217)	-0.030 (0.075)	-0.802*** (0.218)	-0.167*** (0.021)	-19.055*** (2.966)
REI	-0.167* (0.099)				
REI*FD	-6.220** (2.568)				
IRHP		-0.943** (0.391)			
IRHP*FD		-0.010** (0.004)			
IWE			-963** (0.411)		
IWE*FD			-0.101*** (0.011)		
ISE				-0.037** (0.016)	
ISE*FD				-0.096*** (0.009)	
IBE					-1.191*** (0.175)
IBE*FD					-0.924*** (0.156)
Constant	-4.883*** (0.652)	-0.042 (0.263)	1.358 (2.237)	0.323 (0.260)	-3.730** (1.670)
No. Obs.	1081	1081	1081	1081	1081
Instruments/Group	42/47	32/47	43/47	43/47	42/47
Hansen Statistics	31.663	17.674	29.107	40.985	33.5993
Note: ***, **, and * are for 1%, 5%, and 10% significance level. Standard errors in parentheses.					

Variable	REI	IRHP	IWE	ISE	IBE
	M1	M2	M3	M4	M5
Hansen P-value	0.484	0.477	0.661	0.225	0.297
Note: ***, **, and * are for 1%, 5%, and 10% significance level. Standard errors in parentheses.					

5.2.3 Granger causality results

The literature widely recognized that the presence of a link between two variables does not automatically designate a causal association between them (Abendin et al., 2024; Bunje et al., 2022). The current study used Xiao et al. (2023) panel Granger causality test to examine the causal link between financial development (FD), sustainable trade development, and renewable energy investment (REI). This study initially created a separate model for sustainable trade development (SUSTD) using each explanatory variable. Subsequently, the study investigated whether the explanatory variables collectively influence SUSTD. In this study, we chose a maximum lag of 2 based on the specific characteristics of the time series we used. Table 9 presents the findings of the enhanced panel Granger causality test from Xiao et al. (2023). We reject the null hypothesis at the 1% significance level based on the results reported in Table 9, which show that financial development and investments in renewable energy do not contribute to sustainable trade development. These findings suggest that previous values of renewable energy investment and financial development have a more substantial predictive power for sustainable trade development compared to previous values of sustainable trade development alone. The justification for the REI result is evident due to its role in promoting a transition to a renewable energy economy. It achieves this by incentivizing the development and adoption of eco-friendly technology, mitigating environmental risks, and optimizing resource utilization. The FD findings are credible because they provide funds for investment in renewable energy activities. These funds incentivize companies to adopt environmentally friendly manufacturing methods, which can reduce carbon emissions. Ultimately, this promotes the growth of sustainable trade practices. Table 9 shows that the null hypothesis, which suggests that the explanatory factors do not collectively have a Granger-causal effect on sustainable trade, is rejected at a significance level of 1%.

Table 9
The Juodis-Karavias-Sarafidis Panel Granger causality test

Null Hypothesis	HPJ Wald test	HPJ p-value_
REI does not Granger-cause SUSTD	15.578***	0.000
FD does not Granger-cause SUSTD	10.177***	0.006
POP does not Granger-cause SUSTD	32.766***	0.000
ECO does not Granger-cause SUSTD	782.067***	0.000
GDP does not Granger-cause SUSTD	6.782**	0.034
IMP does not Granger-cause SUSTD	53.385***	0.000
EXP does not Granger-cause SUSTD	4.855*	0.088
INTRATE does not Granger-cause SUSTD	1.380	0.502
Combined selected covariates do not Granger-cause SUSTD	53.971***	0.000
Note: ***, **, and * are for 1%, 5%, and 10% significance level.		

5.3 Marginal effects results

This section examines the impact of renewable energy investment on sustainable trade development at average financial development levels. It considers the marginal effect of the interaction term and examines how renewable energy investment affects sustainable trade growth. Table 10 presents the findings, together with coefficients and standard errors estimated for the financial development quantiles of 10th, 25th, 50th, 75th, and 95th. It is worth noting that if the computed coefficients of the percentile values are found to be statistically significant, this will reveal the specific percentile level at which investments in renewable energy have an impact on the development of sustainable trade, provided that financial development improves. Table 10 shows that renewable energy investments significantly contribute to sustainable trade development, with their influence increasing as the percentiles progress, starting at the 10th percentile. Specifically, the coefficients suggest that if financial development is at its mean values, renewable energy investment promotes sustainable trade development by a range of 0.756% to 1.853% across the quantiles, as shown in Table 10 at the 1% significance level, holding all else constant.

Furthermore, Table 10 reports threshold effects based on the quantile regression method. The threshold effect shows the threshold at which financial development modulates renewable energy investment to promote sustainable trade development. The threshold concept helps policymakers identify variables that can be adjusted to achieve desired developmental outcomes. It helps identify cut-off levels for financial development below which an increase in renewable energy investment would have a negative impact on consumption-based carbon emissions. From Table 10, it is observed that the threshold effects occur from the 50th to the 95th quantiles. Therefore, we computed the financial development threshold value for the 50th quantile by dividing the renewable energy investment coefficient by the interaction term's coefficient: $[-0.056/0.584] = 0.096$. This indicates that a certain level of 0.096% financial development is required to counteract the effect of renewable energy investment. Thus, 0.096% of financial development is required to complement renewable energy investment (REI) to boost sustainable trade development. For the 75th quantile, the threshold effect is: $[-0.072/0.593] = 0.122$, and that of the 95th quantile is: $[-0.229/5.293] = 0.043$. These findings suggest that beyond specific thresholds in each quantile (75th and 95th), financial development enhances renewable energy investment's ability to reduce consumption-based carbon emissions by 0.122% and 0.043%, respectively. This effect supports

sustainable trade development. By pinpointing the critical levels at which financial development influences the relationship between renewable energy investment and consumption-based carbon emissions, this study makes a significant contribution to the literature on both consumption-based emissions and sustainable trade development.

Table 10
Marginal effect of renewable energy investment on sustainable trade as financial development improves.

Quantile/percentile	10th	25th	50th	75th	95th
FD mean values	0.470	0.628	0.754	0.930	1.091
Marginal effects	-0.756***	-1.034***	-1.257***	-1.568***	-1.853***
	(0.289)	(0.385)	(0.461)	(0.569)	(0.667)
FD	0.074*	0.031	0.042*	0.064**	0.150*
	(0.038)	(0.042)	(0.025)	(0.030)	(0.081)
POP	0.095***	0.100***	0.103***	0.102***	0.890***
	(0.002)	(0.002)	(0.002)	(0.001)	(0.005)
ECO	-0.018***	-0.004	0.001	-0.034***	-0.140***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.025)
GDP	-0.001	0.001	-0.004	-0.015***	-0.031*
	(0.007)	(0.007)	(0.005)	(0.005)	(0.018)
IMP	0.044**	0.048***	0.054***	0.064***	0.044***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.007)
EXP	-0.074	-0.019	0.022**	-0.020**	-0.097
	(0.047)	(0.017)	(0.010)	(0.100)	(0.065)
INTRATE	-0.032	-0.314***	-0.395***	-0.533***	-0.983***
	(0.135)	(0.051)	(0.083)	(0.060)	(0.171)
REI	-0.019	-0.031	-0.056***	-0.072***	-0.229***
	(0.022)	(0.022)	(0.018)	(0.020)	(0.069)
REI*FD	0.167	0.312	0.584*	0.593*	5.293***
	(0.630)	(0.351)	(0.306)	(0.359)	(1.384)
Threshold effect	n/a	n/a	0.096	0.121	0.043
Observations	1081	1081	1081	1081	1081
Note: ***, **, and * are for 1%, 5%, and 10% significance level. n/a denotes not applicable.					

6. Conclusion and policy implications

6.1 Conclusion

This study examines the role of renewable energy investment and financial development and their interaction effects in sustainable trade development for 47 Sub-Saharan Africa (SSA) economies over the period 2000–2022. The current study utilized the PCSE as a baseline estimation technique that controls for cross-sectional dependence, serial correlation, and heteroskedasticity. This study further employed the 2SIV, a robustness check method, to address the issue of endogeneity. The results indicate that targeted renewable energy investment channels (IRHP, IWE, ISE, and IBE) promote sustainable trade development, while their aggregate composite index (REI) worsens sustainable trade development in SSA. The adverse effect of the aggregated renewable energy investment may suggest that composite measures can obscure important technology-specific and channel-specific effects, and that scale-driven renewable energy expansion may generate short-run adjustment costs or inefficiencies that outweigh sustainable trade-related benefits. The estimated coefficients further reveal that financial development promotes sustainable trade development and attenuates the adverse effects of aggregate renewable energy investment on sustainable trade development in SSA. This implies that deeper and more efficient financial systems enhance the capacity of economies to translate renewable energy investments into sustainable trade development gains. Moreover, the threshold analysis showed the threshold at which financial development may influence the effects of renewable energy investment on sustainable trade development; we add to the body of work on sustainable trade development. The findings indicate that investments in renewable energy either improve or worsen trade depending on whether financial development is above or below a particular threshold. In addition, the results suggest that economic growth (GDP), population (POP), and imports (IMP) worsen sustainable trade development in SSA economies, while exports (EXP), eco-innovation (ECO), and interest rates (INTRATE) promote sustainable trade

development in SSA countries. Also, the Granger-causality test showed that renewable energy investment and financial development have a predictive power of sustainable trade development in the SSA region.

6.2 Policy Implications

Regarding policy implications, the study results indicate that sub-Saharan African (SSA) countries' investments in renewable energy projects promote sustainable trade development. Given this finding, it is therefore recommended that SSA policymakers should design policies that not only promote renewable energy investment but also address their institutional constraints that may derail the full benefits of renewable energy investments. For instance, targeted grants for research and development (R&D) could foster innovation and reduce the costs of renewable technologies, while direct subsidies for renewable energy producers can accelerate adoption, provided that mechanisms are in place to ensure transparency and accountability. Moreover, our results further contribute to policy debates by suggesting that financial development is not only a direct driver of sustainable trade development but also a critical transmission channel through which renewable energy investments translate into trade gains in Sub-Saharan Africa. Findings indicate that in weak institutional environments, renewable energy investments alone do not achieve sustainable trade outcomes without robust financial systems. The study recommends that policymakers should undertake complementary reforms, including improved green finance regulations and export-oriented green credit facilities, to harness sustainable trade benefits of renewable energy investments. This cohesive policy approach is central for Sub-Saharan Africa, where governance issues and financing risks hinder the effectiveness of isolated renewable energy policies. This highlights the importance of strong financial institutions to environmentally friendly international trade.

As far as we know, this study is the first to determine the impact of financial development on the relationship between renewable energy investment and sustainable trade development in Sub-Saharan Africa (SSA). Nevertheless, it is essential to recognize that findings from this study alone may not be sufficient for policymakers. Hence, it is crucial for future research to thoroughly examine individual and cross-national contexts, conduct theoretical analysis, and conduct comparative studies in both developing and developed countries. This will enhance the understanding of this relationship and provide policymakers with more substantial data.

Declarations

Author Contribution

A. Conceptualization, Investigation, Writing - original draft, Methodology, Validation, Visualization, Writing - review & editing, Software, Formal analysis, Data curation; B. Supervision, Funding acquisition, Resources; C. Project administration, Resources.

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Data Availability

The data and codes used in this study have been deposited in the Mendeley Data repository and are publicly available at the following URL <http://dx.doi.org/10.17632/srz3j9vp4d>.

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Figures

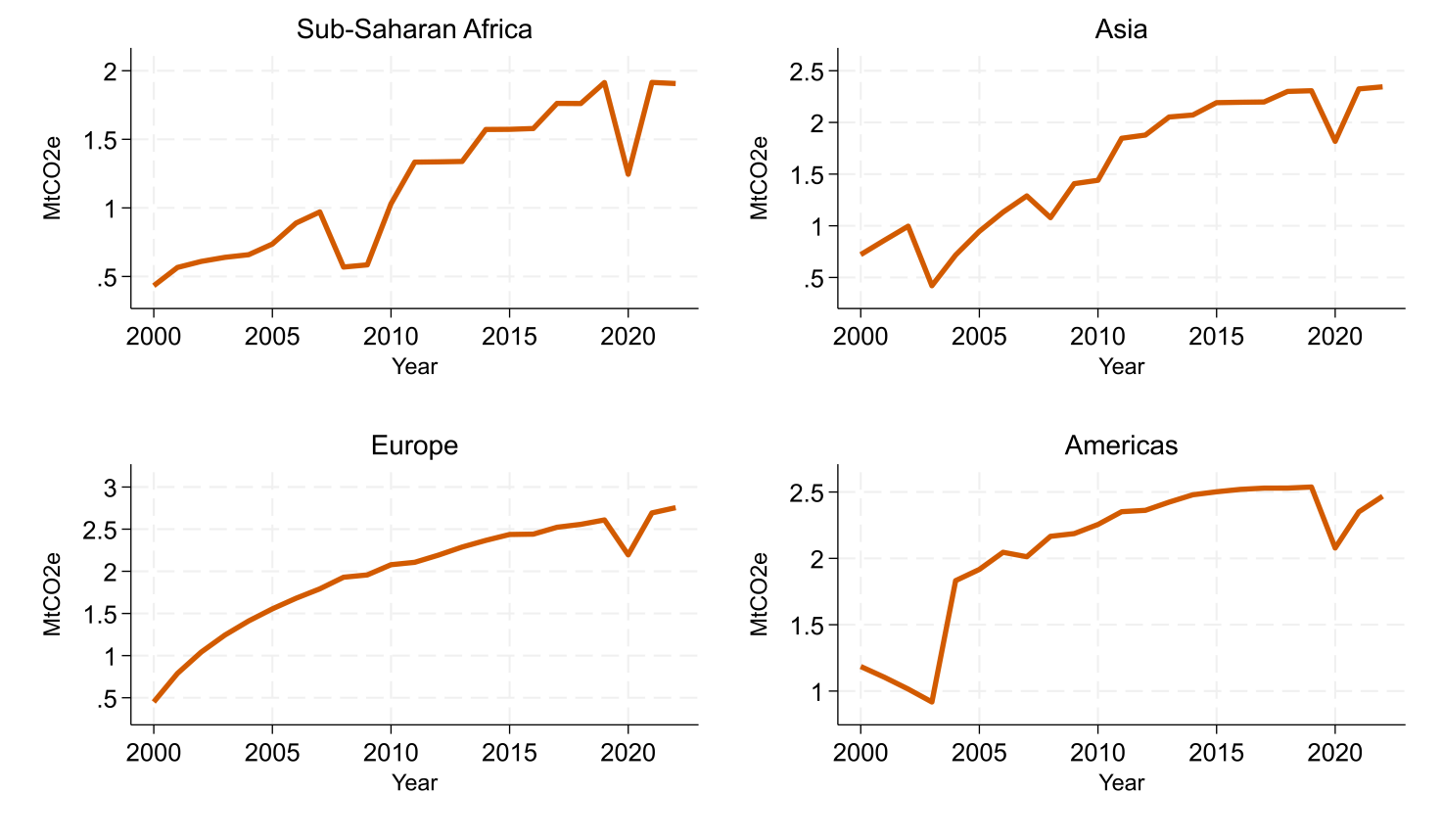


Figure 1

Consumption-based greenhouse gas (GHG) emissions across regions. Source: Authors based on Global Carbon Atlas (2024).

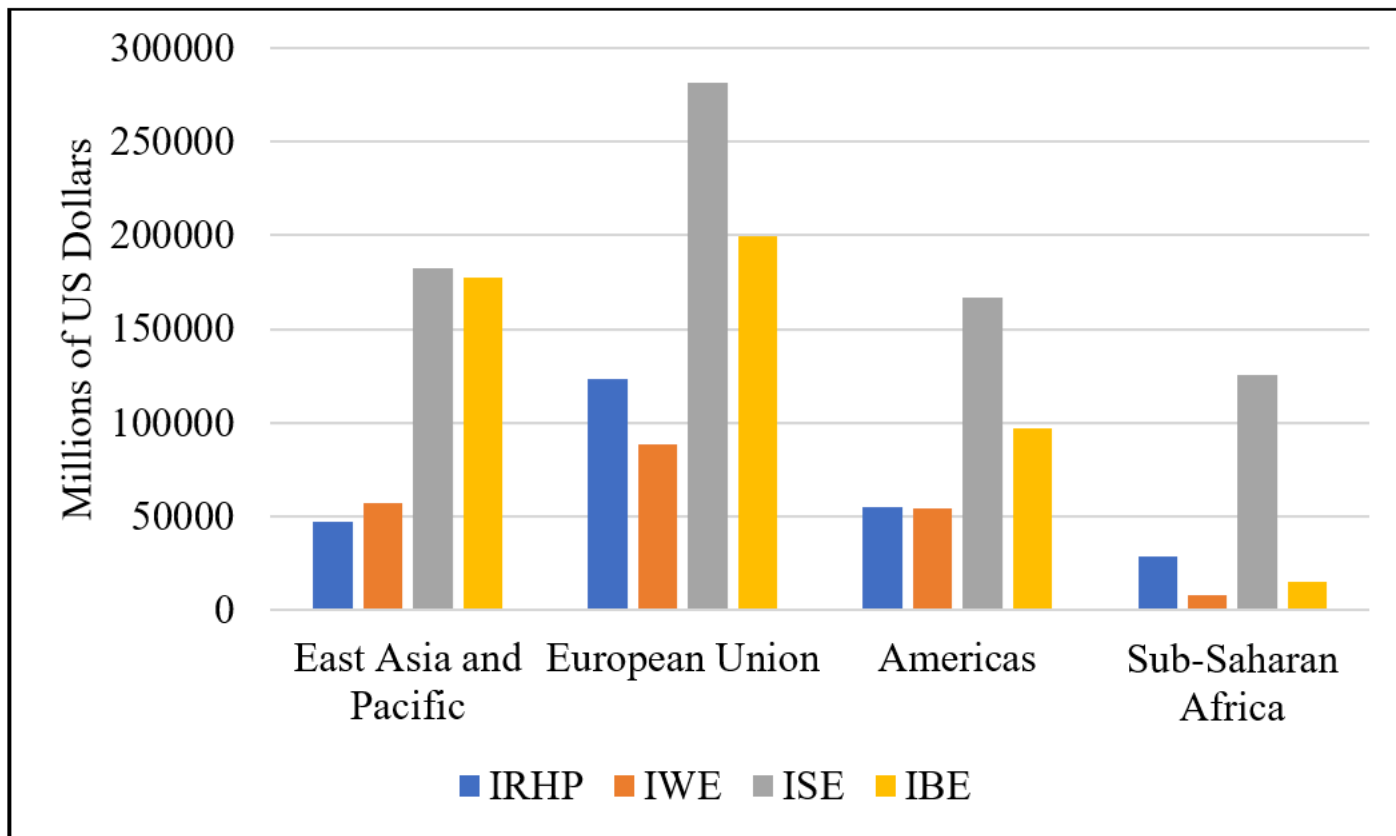


Figure 2

Average renewable energy investment (investment in renewable hydropower (IRHP), investment in wind energy (IWE), investment in solar energy (ISE), and investment in bioenergy (IBE)) across regions, 2022. Source: Authors based on WDI and IMF

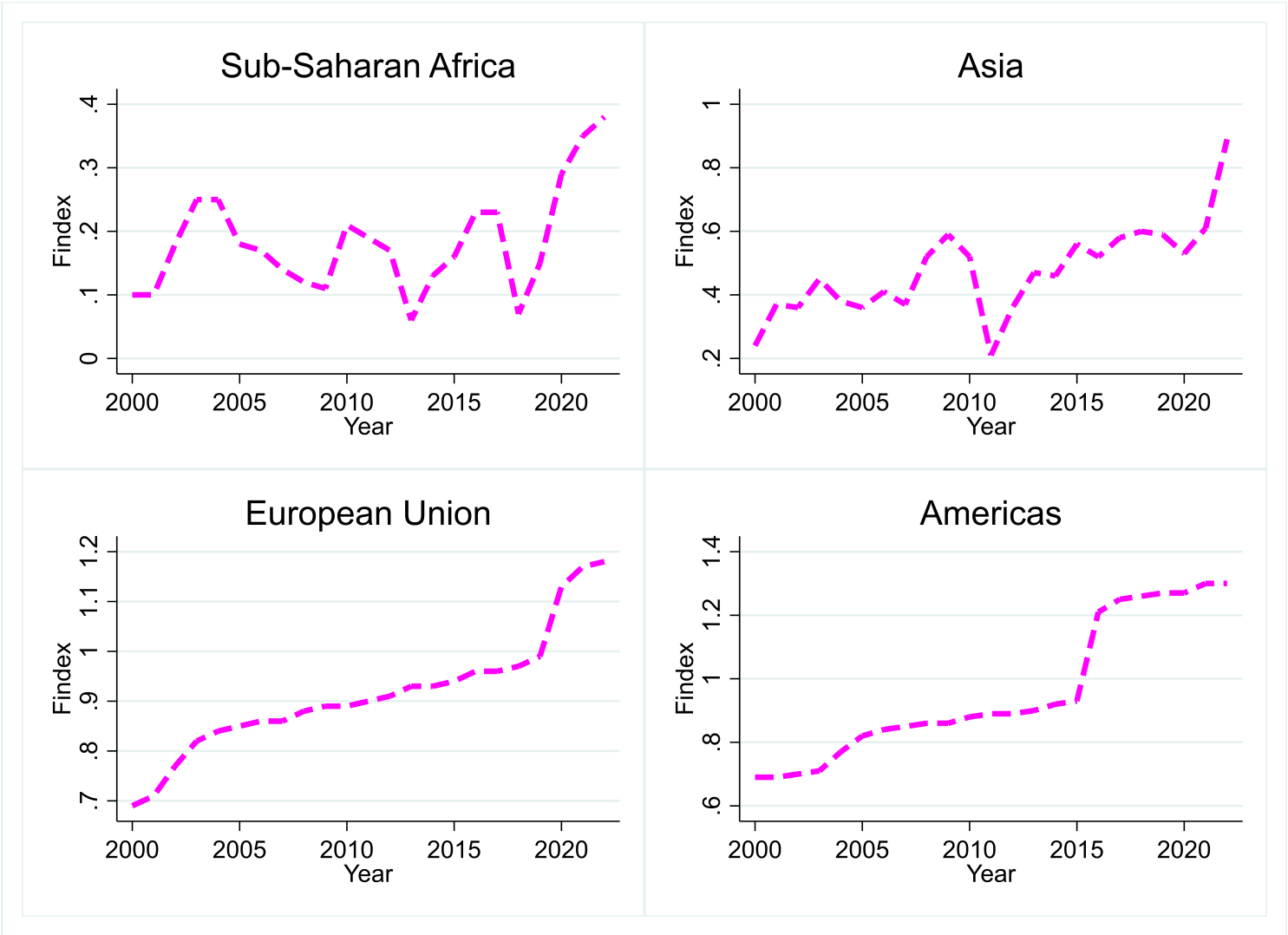


Figure 3

Average financial development index, 2022. Source: Authors based on IMF data