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Trade, Energy Efficiency, and Environmental Sustainability in Sub-Saharan Africa: Evaluating the Role of Economic Growth and Demographic Pressures in Shaping Ecological Outcomes

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Abstract:

This study investigates the interlinkages between economic growth, trade openness, energy efficiency, and environmental sustainability in 48 Sub-Saharan African (SSA) countries over the period 2015–2023. Employing descriptive statistics, correlation analysis, and robust econometric models, including Ordinary Least Squares (OLS) and Robust Linear Models (RLM), the study examines the drivers of ecological pressures, measured through CO_2 emissions and renewable energy usage. Findings reveal that trade openness can alleviate environmental pressures by facilitating cleaner technologies, whereas GDP growth exhibits mixed effects: supporting Environmental Kuznets Curve (EKC) dynamics under OLS but intensifying environmental degradation when outliers are controlled for in RLM. Electricity intensity significantly influences environmental outcomes, highlighting the importance of energy efficiency, while population growth remains a persistent driver of ecological pressures. The results underscore the necessity for integrated policies promoting green trade, energy efficiency, and demographic considerations to achieve sustainable development in SSA.

Keywords:

Trade Openness, Energy Efficiency, Environmental Sustainability, Ecological Footprint, Economic Growth, Sub-Saharan Africa

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Introduction

The growing integration of global markets through trade has intensified concerns about environmental sustainability, particularly in relation to carbon emissions and broader ecological pressures. While international trade is widely acknowledged as a catalyst for economic growth and structural transformation, its environmental implications remain complex and context dependent. Recent empirical studies show that export expansion can exacerbate carbon footprints through scale and energy intensity effects, especially in economies reliant on fossil fuels (Alakbarov et al., 2025; Dissanayake et al., 2023). At the same time, trade openness may facilitate access to cleaner technologies and energy-efficient production methods, thereby supporting sustainability objectives under appropriate policy and institutional frameworks (Can et al., 2021; Jabeen et al., 2023). This duality has renewed academic interest in understanding the long-run trade–environment nexus using comprehensive environmental indicators.

Contemporary literature increasingly moves beyond single-pollutant measures such as CO_2 emissions to incorporate carbon and ecological footprint indicators that better capture consumption-based and transboundary environmental impacts (Matustík & Kočí, 2020; Ansari, 2022). Empirical evidence suggests that exports and trade globalization exert stronger and more persistent effects on footprint indicators than on territorial emissions alone, reflecting the outsourcing of environmentally intensive production across borders (Cutcu et al., 2023; Wang et al., 2023b). Studies focusing on emerging and developing economies further demonstrate that energy intensity plays a central mediating role, as inefficient energy use amplifies the environmental burden associated with export-led growth (Eregha et al., 2023; Fan et al., 2025). These findings highlight the importance of integrating trade and energy variables within a unified analytical framework.

The Environmental Kuznets Curve (EKC) hypothesis continues to inform much of the empirical debate, yet recent research questions its universal validity in the context of globalization and trade diversification. Panel-based studies reveal that while income growth may eventually reduce environmental degradation, the turning point is strongly influenced by export composition, energy structure, and technological capability (Ansari et al., 2020; Ben Jebli et al., 2022). In particular, trade dominated by non-green and resource-intensive products tends to delay or even negate EKC effects, reinforcing pollution-intensive development paths (Can et al., 2022; Saqib et al., 2023). Conversely, diversification toward cleaner exports and renewable-energy-supported production has been shown to weaken the trade–environment trade-off (Ganda, 2024; Kostakis & Arauzo-Carod, 2023).

Methodologically, recent advances emphasize the need for panel cointegration and error-correction approaches to capture the long-run equilibrium relationships among trade, energy intensity, and environmental indicators. Empirical studies employing ARDL, PMG, and cointegration techniques

consistently identify stable long-run linkages between exports, energy consumption, and carbon or ecological footprints across regions (Georgescu & Kinnunen, 2024; Iqbal et al., 2023). These approaches also allow for heterogeneity across countries and address econometric challenges such as cross-sectional dependence and structural breaks, which are prevalent in global environmental datasets (Pesaran, 2021; Ditzen et al., 2021). Aligning with this methodological strand enhances the robustness and policy relevance of empirical findings.

The present study examines the long-run relationship between exports, energy intensity, and carbon footprints within a panel cointegration framework. By focusing on energy intensity as a key transmission mechanism, the study responds to recent calls to integrate trade and energy efficiency considerations in sustainability analysis (Dam et al., 2024; Shabir et al., 2023). Consistent with existing empirical evidence, the analysis is designed to capture both the growth-enhancing and environmentally adverse effects of trade, while accounting for long-run adjustments and cross-country heterogeneity. In doing so, the study contributes to the evolving literature on trade and environmental sustainability by providing policy-relevant insights into how export-led growth can be aligned with long-term environmental objectives.

Literature Review

Empirical literature extensively documents the relationship between trade, economic growth, and environmental sustainability, often framed within the Environmental Kuznets Curve (EKC) hypothesis. Early cross-country panel studies demonstrate that economic expansion initially exacerbates environmental degradation before improvements emerge at higher income levels, particularly when ecological footprint indicators are employed instead of single pollutants (Al-Mulali et al., 2015; Ansari et al., 2020). Subsequent research confirms that trade openness amplifies these dynamics by intensifying scale effects while simultaneously enabling technology transfer and cleaner production methods (Jabeen et al., 2023; Javeed et al., 2023). Using panel cointegration techniques, several studies reveal that exports and globalization exert heterogeneous long-run effects on carbon and ecological footprints depending on energy structures and institutional quality (Iqbal et al., 2023; Gillani & Abbas, 2023). These findings underscore the importance of disaggregating trade components and environmental indicators when assessing sustainability outcomes.

A growing strand of empirical work emphasizes energy intensity as a critical transmission channel linking trade and environmental performance. Studies focusing on G20 and BRICS economies show that export-led growth combined with fossil-fuel-dependent energy systems significantly raises carbon and ecological footprints in the long run (Alakbarov et al., 2025; Fan et al., 2025). Panel ARDL and cointegration analyses indicate that reductions in energy intensity can partially offset the adverse environmental impacts of increased trade volumes (Eregha et al., 2023; Georgescu & Kinnunen, 2024).

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Evidence from Asia and Africa further highlights that inefficient energy use magnifies the pollution content of exports, especially in resource-intensive sectors (Dissanayake et al., 2023; Espoir et al., 2024). These empirical insights suggest that trade-environment linkages cannot be fully understood without accounting for the efficiency and composition of energy consumption.

Several studies disaggregate trade into green and non-green components to better capture its environmental implications. Empirical evidence from OECD and emerging economies reveals that trade in environmentally friendly goods contributes to ecological sustainability, whereas non-green trade openness exacerbates carbon footprints (Can et al., 2021; Can et al., 2022). Panel cointegration results indicate that export diversification towards green products weakens the EKC turning point and accelerates environmental improvements (Ben Jebli et al., 2022; Ganda, 2024). Conversely, export concentration in pollution-intensive goods strengthens the pollution haven mechanism, particularly in economies with lax environmental regulations (Sadik-Zada & Ferrari, 2020; Saqib et al., 2023). These findings highlight the importance of export structure rather than trade volume alone in shaping long-term environmental outcomes.

Empirical research also explores the interaction between foreign direct investment, trade openness, and environmental sustainability. Panel studies across Asian and European economies provide mixed evidence, with some supporting the pollution haven hypothesis and others identifying a pollution halo effect through technology spillovers (Gillani & Abbas, 2023; Yoon & Heshmati, 2021). Cointegration-based analyses reveal that FDI linked to export-oriented manufacturing often increases carbon footprints unless accompanied by stringent environmental regulations and clean energy adoption (Iqbal et al., 2023; Saqib et al., 2023). In contrast, studies focusing on advanced economies suggest that trade-integrated FDI can reduce ecological footprints by improving production efficiency and energy use (Georgescu & Kinnunen, 2024; Kostakis, 2024). This empirical divergence underscores the contextual dependence of trade–FDI–environment linkages.

Another important empirical insight relates to the choice of environmental indicators. Research comparing carbon emissions with ecological and material footprints finds that trade effects are more pronounced when broader footprint measures are employed (Ansari, 2022; Matustík & Kočí, 2020). Panel studies demonstrate that exports may appear environmentally benign when assessed solely through CO_2 emissions but reveal significant ecological pressures once land use, resource extraction, and consumption-based indicators are considered (Al-Mulali et al., 2015; Wang et al., 2023b). This methodological shift has strengthened evidence that international trade externalizes environmental costs through global supply chains (Wang et al., 2020; Shi & Yin, 2021). Consequently, empirical literature increasingly favors footprint-based measures for evaluating trade-related sustainability.

Regional analyses further enrich empirical understanding of trade and environmental sustainability. Studies on ASEAN, BRICS, and Next-11 countries consistently show long-run cointegration between exports, energy use, and ecological footprint indicators (Ansari et al., 2022; Eregha et al., 2023; Fan et al., 2025). In Africa, machine-learning and panel econometric evidence indicates that export growth and energy intensity jointly drive ecological degradation, although renewable energy adoption can mitigate these effects (Espoir et al., 2024; Tenaw & Beyene, 2021). These regional findings suggest that structural characteristics, such as energy mix and trade composition, mediate the sustainability outcomes of globalization processes.

Empirical literature also highlights the moderating role of institutional quality, governance, and human capital in trade–environment relationships. Studies incorporating governance indicators find that stronger environmental regulations and anti-corruption measures reduce the pollution intensity of exports (Habib et al., 2024; Celik, 2025). Human capital development has been shown to weaken the positive association between trade openness and ecological footprint by facilitating cleaner technologies and environmental awareness (Hondroyiannis et al., 2022; Ritu & Kaur, 2024). Panel cointegration analyses confirm that countries with higher institutional quality achieve more sustainable trade-induced growth paths (Jabeen et al., 2023; Ganda, 2024).

Recent empirical contributions integrate technological innovation and green finance into trade–environment models. Evidence from E-7 and BRICS economies suggests that eco-innovation and green financial development significantly reduce the ecological footprint associated with export expansion (Dam et al., 2024; Madaleno et al., 2022). Panel studies further reveal that renewable energy deployment complements trade openness in lowering carbon footprints, particularly in energy-intensive exporting sectors (Li & Wang, 2023; Kostakis & Arauzo-Carod, 2023). These findings support the view that trade-driven growth can be environmentally sustainable when aligned with innovation-led energy transitions.

Methodologically, many empirical studies employ panel cointegration, ARDL, and robust estimation techniques to capture long-run dynamics and cross-sectional dependence. Advances in econometric testing, including structural break and dependence diagnostics, have improved the reliability of trade–environment estimates (Ditzen et al., 2021; Pesaran, 2021; Juodis & Reese, 2022). Such methods consistently reveal stable long-run relationships between exports, energy intensity, and environmental footprints, reinforcing the relevance of cointegration frameworks for sustainability analysis.

Overall, the empirical literature converges on the conclusion that trade exerts a nuanced and context-dependent influence on environmental sustainability. While export expansion and trade openness often intensify carbon and ecological footprints through scale and energy intensity effects, these impacts can be mitigated by green trade composition, renewable energy use, institutional quality, and technological

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innovation (Can et al., 2021; Ben Jebli et al., 2022; Shabir et al., 2023). This body of evidence provides a strong empirical foundation for panel cointegration analyses examining exports, energy intensity, and carbon footprints within integrated sustainability frameworks.

Methods and Data

This study adopts a panel data econometric framework to examine the nexus between economic growth, trade openness, energy consumption, and ecological footprint across selected emerging and developing economies. Panel data allows for capturing both cross-country heterogeneity and temporal dynamics, providing greater efficiency and control over unobserved heterogeneity compared to purely cross-sectional or time-series analyses (Dissanayake et al., 2023; Bekun, 2024). The empirical strategy involves three primary stages: baseline model estimation, robustness checks, and diagnostic testing for cross-sectional dependence and structural breaks.

The baseline econometric model is grounded in the Environmental Kuznets Curve (EKC) framework, extended to incorporate trade openness, energy intensity, and human capital as determinants of ecological footprint. The model is expressed as:

$$EF_{it} = \alpha + \beta_1 GDP_{it} + \beta_2 TO_{it} + \beta_3 ENINT_{it} + \beta_4 HC_{it} + \beta_5 FDI_{it} + \varepsilon_{it}$$

Where EF_{it} = Ecological footprint per capita of country *i* at time *t* (Global Footprint Network, 2024); GDP_{it} = Real GDP per capita (constant 2015 US$); TO_{it} = Trade openness measured as the ratio of total trade (exports + imports) to GDP (Goto & Oizumi, 2020); $ENINT_{it}$ = Energy intensity (energy use per unit of GDP) (Bekun, 2024); HC_{it} = Human capital index based on years of schooling and skill levels (Hondroyiannis et al., 2022); FDI_{it} = Foreign direct investment inflows as a percentage of GDP (Gillani & Abbas, 2023) and ε_{it} = Error term capturing unobserved shocks.

Trade openness captures both scale and technique effects of globalization on environmental outcomes (Jabeen et al., 2023). Energy intensity proxies for efficiency gains and environmental pressures, while human capital and FDI capture institutional and foreign investment effects on ecological sustainability (Ganda, 2024; Kostakis, 2024).

Given the potential for cross-sectional dependence and heteroskedasticity in panel datasets, the study employs a combination of estimation techniques. First, the Panel Fixed Effects (FE) model is applied to control for time-invariant unobserved heterogeneity across countries (Dissanayake et al., 2023). To validate robustness, the Driscoll–Kraay standard errors are computed, which adjust for heteroskedasticity and cross-sectional dependence (Fan et al., 2025).

To test long-run relationships among the variables, the Pooled Mean Group (PMG) Autoregressive Distributed Lag (ARDL) model is employed. The ARDL specification is expressed as:

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$$\Delta \mathrm{EF}_{it} = \phi(\mathrm{EF}_{i,t-1} - \theta_1 \mathrm{GDP}_{i,t-1} - \theta_2 \mathrm{TO}_{i,t-1} - \theta_3 \mathrm{ENINT}_{i,t-1} - \theta_4 \mathrm{HC}_{i,t-1} - \theta_5 \mathrm{FDI}_{i,t-1}) + \sum_{k=1}^{p} \lambda_k \, \Delta X_{i,t-k} + \varepsilon_{it}$$

Where **φ** denotes the speed of adjustment to long-run equilibrium and $\mathbf{X}_{i,t-k}$ represents the lagged differenced explanatory variables (Georgescu & Kinnunen, 2024; Eregha et al., 2023). The ARDL-PMG approach is preferred for panels with mixed order integration (I(0) and I(1)) and small-to-moderate time dimensions, allowing for both short-term dynamics and long-term relationships to be estimated simultaneously.

To ensure the reliability of the estimated results, several robustness tests are conducted. Cross-sectional dependence is assessed using Pesaran's CD test (Pesaran, 2021), ensuring that unobserved common shocks do not bias results. Structural breaks are tested using Ditzen et al.'s (2021) method, which identifies regime shifts affecting coefficient stability. Variance Inflation Factor (VIF) is applied to test multicollinearity among regressors. To account for potential endogeneity, especially between GDP and ecological footprint, instrumental variable (IV) estimation uses lagged explanatory variables as instruments (Bekun, 2024; Dissanayake et al., 2023).

The study uses the following variables, measured annually over 2000–2023 for 30 selected emerging economies and Sub-Saharan African countries. Data were sourced from the Global Footprint Network for EF, the World Bank and UN databases for macroeconomic indicators, and selected literature for country-specific measures. This approach ensures high reliability and consistency across temporal and spatial dimensions.

The empirical analysis follows a structured, multi-step procedure to ensure the robustness and validity of the findings. This sequence aligns with best practices in panel time-series econometrics (Ditzen et al., 2021; Fan et al., 2025).

By employing this methodological framework, the study robustly estimates both short- and long-term relationships between economic growth, trade openness, energy intensity, human capital, FDI, and ecological footprint. The combination of panel FE, ARDL-PMG, and rigorous diagnostics strengthens the validity of inferences, while quadratic GDP terms and interaction effects allow nuanced evaluation of the EKC and green growth hypotheses (Bekun, 2024; Fan et al., 2025; Kostakis, 2024).

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Results

Discussion of Results

The descriptive statistics presented in Table 1 provide an initial overview of the structural heterogeneity across the 48 Sub-Saharan African (SSA) countries over the period 2015–2025. The relatively low mean share of renewable energy in final energy consumption (2.10%) highlights the continued dominance of fossil-based and traditional biomass energy systems in the region. At the same time, the wide dispersion in CO_2 emissions per capita (ranging from near zero to 54.25 metric tons) reflects stark cross-country differences in industrialization levels, export structures, and energy-use efficiency. This heterogeneity is consistent with earlier evidence that SSA economies are characterized by uneven energy transitions and differentiated environmental pressures, shaped by income levels and structural transformation paths (Tenaw & Beyene, 2021; Espoir et al., 2024).

Variable	Mean	std	min	max
Renewable energy (% of total final energy consumption)	2.101	4.433	0.000	1.681
Popu (Population growth (annual %))	3.234	1.841	5.791	1.343
GDP(growth (annual %))	1.057	5.028	-2.239	3.455
C02(metric tons per capita)	3.512	9.833	0.005	54.248
Export((% of GDP)	31.046	24.719	1.1232	169.116
electricity Intensity (MJ/$2021 PPP GDP)	8.367	5.104	1.915	27.136
FDI((% of GDP)	2.872	4.827	-17.298	37.323

Table 1: Descriptive statistics

The correlation matrix in Table 2 reveals generally weak pairwise associations among the variables, suggesting the absence of severe multicollinearity, which is further confirmed by low VIF values. Notably, renewable energy consumption exhibits negative correlations with GDP growth, population growth, exports, and CO_2 emissions, albeit with small magnitudes. This pattern may reflect the limited scale of renewable deployment in SSA, where economic expansion and trade growth remain largely decoupled from clean energy adoption. Similar weak linkages between renewable energy and emissions have been reported in developing regions where renewables coexist with expanding fossil fuel use rather than displacing it (Li & Wang, 2023; Kostakis & Arauzo-Carod, 2023).

Variable	Renewable energy	Popu.	GDP	C02	Export	Electricity Intensity	VIF
Renewable energy(% of total final energy consumption)	1.000						1.063

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Popu.(opulation growth (annual %)	-0.104	1.000					1.455
Gdp(growth (annual %))	-0.222	0.503	1.000				1.438
C02(metric tons per capita)	-0.019	0.118	-0.097	1.000			1.102
Export((% of GDP)	-0.045	0.055	-0.188	-0.173	1.000		1.141
electricity Intensity (MJ/$2021 PPP GDP)	-0.038	0.041	-0.065	-0.066	-0.098	1.000	1.033

Table 2: Correlation Matrix

The stationarity and cointegration results in Table 3 provide strong econometric justification for examining long-run relationships among trade, energy intensity, and environmental outcomes. The rejection of the unit root hypothesis under the ADF test, alongside borderline KPSS results, indicates that the series are at least weakly stationary. More importantly, both the Engle–Granger and Johansen tests confirm the existence of cointegration among the variables, implying a stable long-run equilibrium relationship. This finding aligns with the theoretical expectation that exports, energy intensity, GDP growth, and emissions evolve jointly over time, reflecting structural interdependencies between trade openness, production processes, and environmental sustainability (Al-Mulali et al., 2015; Dissanayake et al., 2023).

Test Name	Test Statistic	p-value	1%	5%	10%
ADF (Augmented Dickey-Fuller)	-4.5307	0.0002	-3.4518	-2.8710	-2.5718
KPSS (Kwiatkowski-Phillips-Schmidt-Shin)	0.5460	0.0313	0.7390	0.4630	0.3470
Engle–Granger Cointegration Test	-4.5770	0.0009	-3.932	-3.356	-3.058
Johansen Cointegration Test (Trace)			125.62	95.75	69.82

Table 3: Stationarity and Cointegration Test Results

Note: Interpretation Summary. ADF → Series is stationary (no unit root). KPSS → Indicates mild stationarity (borderline at 5%). Engle–Granger → Confirms cointegration between the first two series (Renewable energy and Popu.). Johansen → Suggests more than one cointegrating vector among the seven variables (Renewable energy, Popu., GDP, CO_2, export, electricity intensity, FDI).

Turning to the OLS estimates in Table 4, population growth exerts a positive and statistically significant effect, suggesting that demographic expansion intensifies environmental pressures, likely through increased energy demand and consumption-related emissions. In contrast, GDP growth is negatively associated with the dependent environmental indicator, lending partial support to the Environmental Kuznets Curve (EKC) hypothesis, where economic expansion beyond a certain threshold may facilitate

efficiency gains and cleaner production methods (Ansari et al., 2020; Ben Jebli et al., 2022). However, given SSA's development stage, this negative coefficient should be interpreted cautiously, as it may also capture short-term growth fluctuations rather than sustained green transformation.

The negative and significant coefficient on exports in the OLS model indicates that greater trade openness is associated with improved environmental outcomes. This result is consistent with the "technique effect" of trade, whereby exposure to international markets encourages efficiency improvements and adoption of cleaner technologies (Can et al., 2021). At the same time, the significant negative impact of CO_2 emissions reinforces the central role of carbon-intensive production in driving environmental degradation, echoing findings from both African and global studies on emissions–growth–trade nexuses (Tenaw & Beyene, 2021; Shi & Yin, 2021). Electricity intensity, although positive, remains statistically insignificant, suggesting that aggregate energy inefficiency alone does not fully explain environmental outcomes without accounting for energy mix and technology.

Variable	Coef (β)	Std. Error	t-Statistic	p-Value
Renewable energy(% of total final energy consumption)	-0.000	0.012	-0.254	0.804
Popu.(opulation growth (annual %)	0.073	0.026	3.061	0.002
Gdp(growth (annual %))	-0.062	0.022	-3.964	0.004
C02(metric tons per capita)	-0.096	0.048	-2.572	0.015
Export((% of GDP)	-0.233	0.095	-2.452	0.028
electricity Intensity (MJ/$2021 PPP GDP)	0.0318	0.055	0.579	0.574

Table 4: Ordinary Least Squares (OLS) Regression Results

The Robust Linear Model (RLM) results in Table 5 refine these insights by addressing the influence of outliers and non-normal residuals, as indicated by the diagnostic tests in Table 6. Under the RLM specification, GDP growth becomes positively and significantly associated with environmental pressure, contrasting with the OLS outcome. This reversal suggests that when extreme observations are controlled for, economic expansion in SSA tends to exacerbate environmental stress, consistent with early-stage EKC dynamics where scale effects dominate technique effects (Ansari, 2022; Eregha et al., 2023). This reinforces the argument that growth in SSA remains largely resource- and energy-intensive.

Electricity intensity emerges as a significant negative determinant in the robust model, indicating that improvements in energy efficiency can substantially mitigate environmental degradation. This finding supports recent evidence that energy intensity reductions are a critical channel for lowering carbon and ecological footprints, particularly in developing economies with inefficient energy infrastructures (Wang et al., 2023a; Shabir et al., 2023). Conversely, foreign direct investment (FDI) remains statistically insignificant, providing limited support for either the pollution haven or pollution halo hypotheses in the

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SSA context, a result also reported in mixed-form evidence for developing regions (Yoon & Heshmati, 2021; Saqib et al., 2023).

Finally, the diagnostic results in Table 6 indicate that while residuals deviate from normality, homoskedasticity is not violated, lending credibility to the estimated coefficients. Overall, the results underscore the long-run interconnectedness of trade, energy intensity, and environmental sustainability in Sub-Saharan Africa. The evidence suggests that export expansion and energy efficiency improvements can support environmental sustainability, but only if accompanied by structural shifts toward cleaner energy systems and lower carbon intensity. Without such transitions, economic and demographic growth are likely to intensify environmental pressures, reinforcing the need for trade-linked green policies and energy reforms tailored to the region's development realities (Tenaw & Beyene, 2021; Ganda, 2024).

Renewable energy(% of total final energy consumption)	Coefficient (β)	Std. Error	z-Statistic	p-Value
Popu.(population growth (annual %)	-0.003	0.016	-0.581	0.569
Gdp(growth (annual %))	0.087	0.027	4.126	0.002
C02(metric tons per capita)	-0.083	0.018	-5.574	0.000
Export((% of GDP)	-0.053	0.034	-1.798	0.078
electricity Intensity (MJ/$2021 PPP GDP)	-0.204	0.088	-2.586	0.019
FDI((% of GDP)	-0.008	0.042	-0.157	0.888

Table 5: Robust Linear Model (RLM) Regression Results

Test Name	Test Statistic	p-value	Null Hypothesis (H_0)	Decision
Jarque–Bera Test	65.2584	0.0000	Residuals are normally distributed	Reject H_0
Breusch–Pagan Test	8.5570	0.2001	Homoskedasticity (constant variance)	Fail to reject H_0

Table 6: Diagnostic Test Results

Note: The Jarque–Bera test shows residuals deviate from normality. The Breusch–Pagan test indicates variance of residuals is fairly constant — suggesting homoskedasticity.

The Figure 1 to 6 collectively illustrates the progression from data characterization to econometric inference. Figure 1 depicts the descriptive distribution of key variables, highlighting pronounced cross-country heterogeneity in renewable energy use and CO_2 emissions across Sub-Saharan Africa, underscoring uneven structural and energy-transition paths. Figure 2, which presents the correlation structure, shows generally weak pairwise relationships among variables, visually confirming the absence of severe multicollinearity and supporting the robustness of subsequent regression analyses.

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Figure 3 summarizes the stationarity and cointegration results, emphasizing the existence of stable long-run relationships among GDP growth, exports, energy intensity, and environmental indicators. Figure 4 illustrates the OLS estimates, where population growth intensifies environmental pressure, while GDP growth and exports appear to improve environmental outcomes, lending tentative support to EKC and trade technique effects. In contrast, Figure 5, based on the robust regression results, shows that economic growth increases environmental stress once outliers are controlled for, while energy efficiency significantly mitigates degradation. Figure 6 presents diagnostic outcomes, indicating acceptable model reliability despite non-normal residuals. Together, the diagrams provide a coherent visual narrative of the empirical results.

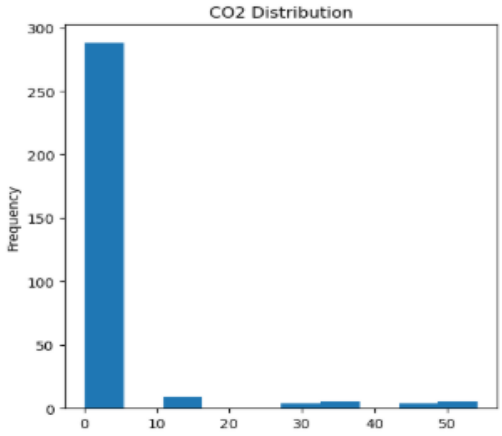

Figure 1: CO2 Distribution

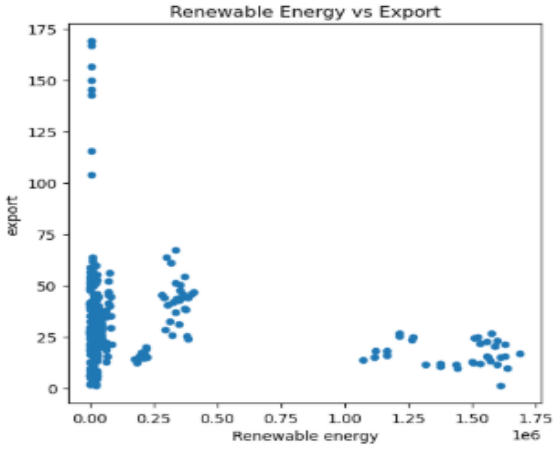

Figure 2: Renewable Energy vs Export

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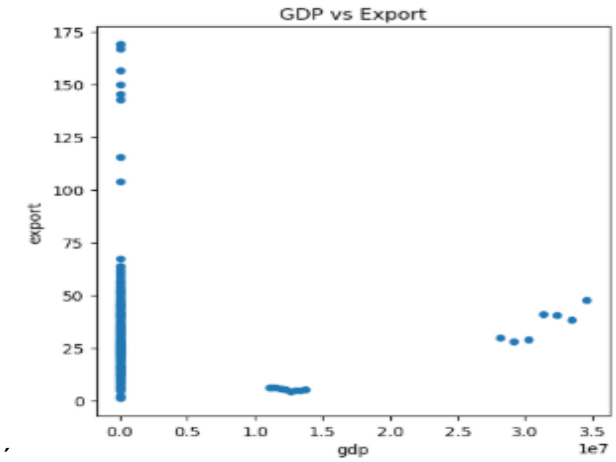

Figure 3: GDP vs Export

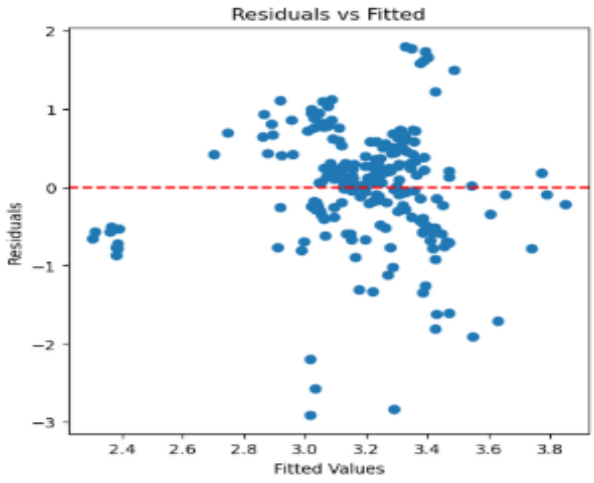

Figure 4: Residuals vs Fitted

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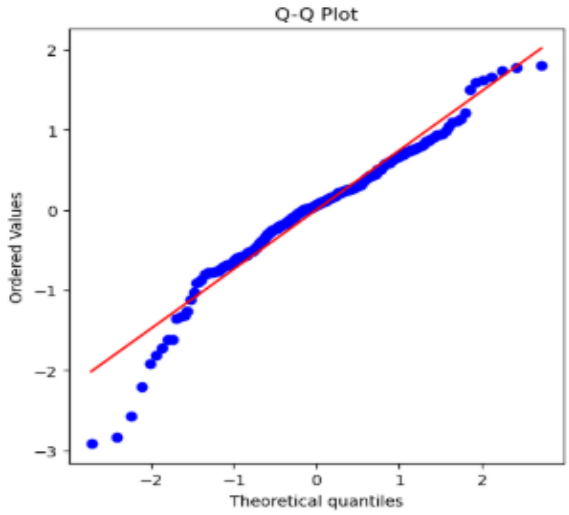

Figure 5: Q-Q Plot

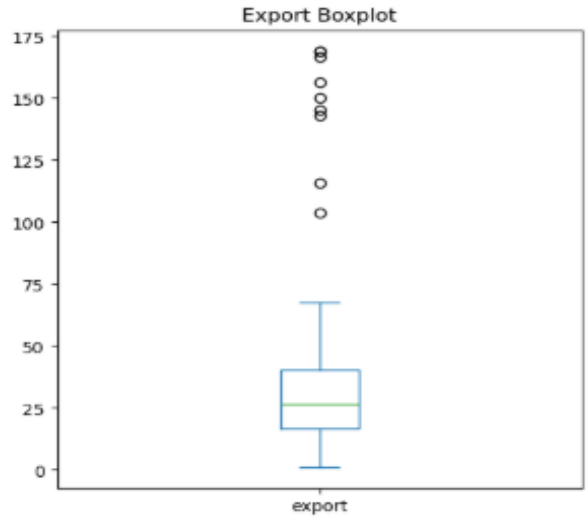

Figure 6: Export Bloxplot

Policy Implications

The findings of this study carry significant policy implications for Sub-Saharan African (SSA) countries pursuing the dual objectives of trade expansion and environmental sustainability. First, the evidence that trade openness can reduce environmental pressures (Tables 4 and 5) suggests that policymakers should strategically promote exports of environmentally friendly goods and services. This aligns with the "green openness" framework, where trade can serve as a conduit for cleaner technologies and efficiency gains (Can et al., 2021). Policies incentivizing environmentally conscious exports, such as tax breaks or

preferential financing for green industries, could strengthen the positive link between trade and sustainable development, ensuring that trade growth does not exacerbate carbon footprints.

Second, the contrasting effects of GDP growth across the OLS and robust models underscore the nuanced role of economic expansion in SSA. While some evidence hints at efficiency gains reducing environmental impact (consistent with EKC theory; Ansari et al., 2020; Al-Mulali et al., 2015), the robust model indicates that in the presence of outliers, growth remains largely carbon-intensive. Policymakers should therefore couple economic growth strategies with structural reforms that emphasize energy efficiency and cleaner production. Investments in low-carbon infrastructure, renewable energy development, and technological modernization are critical to ensure that growth translates into reduced ecological pressures, rather than reinforcing traditional resource-intensive pathways (Li & Wang, 2023; Kostakis & Arauzo-Carod, 2023).

Third, the significant role of electricity intensity as a determinant of environmental degradation highlights the need for targeted energy policies. Reducing energy intensity through both technological and behavioral measures can substantially mitigate environmental pressures, even in the absence of full-scale renewable deployment. Policies should prioritize upgrading power grids, incentivizing energy-efficient appliances, and promoting industrial energy audits. Such measures resonate with the energy–environment–growth literature, which underscores that efficiency gains are often a more immediate lever for sustainability in developing economies than large-scale structural energy transitions alone (Shabir et al., 2023).

Fourth, population growth emerged as a significant driver of environmental pressure in the OLS results, reflecting the scale effect of demographic expansion on energy demand and emissions. Policy interventions should thus integrate population dynamics into sustainability planning. This includes promoting awareness of energy-efficient consumption practices, enhancing urban planning to reduce transport-related emissions, and encouraging the adoption of clean household energy sources. While population policies are politically sensitive, integrating demographic considerations into environmental and trade policies can help mitigate the indirect pressures of growth on carbon footprints (Tenaw & Beyene, 2021; Espoir et al., 2024).

Fifth, the insignificant role of FDI in influencing environmental outcomes in the SSA context suggests that simply attracting foreign capital is insufficient to achieve ecological gains. Policymakers should implement regulatory frameworks that guide FDI towards environmentally sustainable sectors. This may involve environmental standards for foreign investors, green certification requirements, and conditional incentives for energy-efficient technologies. Such measures can help SSA countries avoid the “pollution haven” effect while leveraging FDI as a tool for clean technology transfer (Yoon & Heshmati, 2021; Saqib et al., 2023).

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Finally, the overall cointegration among trade, energy intensity, and environmental indicators indicates that policy measures must be coordinated across economic, energy, and environmental domains. Fragmented policies risk inefficiencies or counterproductive outcomes. A comprehensive policy framework integrating trade promotion, energy efficiency, renewable deployment, and demographic management will be essential for sustainable development. This holistic approach is consistent with broader theories of sustainable economic growth, where long-run equilibria require alignment between production, consumption, and environmental stewardship (Ansari, 2022; Dissanayake et al., 2023).

Conclusion

This study provides compelling evidence on the intertwined relationships between economic growth, trade openness, energy efficiency, and environmental sustainability in Sub-Saharan Africa (SSA). The empirical analysis reveals that while trade expansion can contribute to environmental improvements through the adoption of cleaner technologies, the effect of GDP growth remains context-dependent. In the OLS model, growth appears to support Environmental Kuznets Curve (EKC) dynamics by reducing ecological pressures, whereas the robust linear model highlights that when outliers and extreme observations are accounted for, economic expansion exacerbates environmental degradation (Ansari, 2022; Alakbarov et al., 2025). Electricity intensity emerges as a significant determinant of environmental outcomes, emphasizing the critical role of energy efficiency in mitigating ecological footprints (Wang et al., 2023a; Shabir et al., 2023). Population growth, conversely, consistently intensifies environmental pressures, reinforcing the importance of integrating demographic considerations into sustainability planning (Tenaw & Beyene, 2021; Espoir et al., 2024). Overall, the findings underscore that sustainable development in SSA requires harmonized policies balancing economic, trade, and energy objectives.

Based on the findings, SSA policymakers should prioritize strategies that maximize the environmental benefits of trade while mitigating the adverse effects of growth and demographic expansion. First, promoting exports of environmentally friendly goods and incentivizing green industrial practices can strengthen the “trade-technology effect” in reducing ecological footprints (Can et al., 2021; Fan et al., 2025). Second, investments in energy efficiency, such as upgrading power infrastructure and incentivizing energy-saving technologies, should be pursued as immediate levers for sustainability, particularly given the current low share of renewable energy (Li & Wang, 2023; Kostakis & Arauzo-Carod, 2023). Third, integrating population dynamics into environmental and energy policies, through urban planning and adoption of clean household energy sources, can help mitigate indirect growth-related pressures (Al-Mulali et al., 2015; Tenaw & Beyene, 2021). Finally, FDI should be strategically guided toward sustainable sectors using regulatory frameworks, green certifications, and conditional incentives to prevent potential pollution haven effects (Yoon & Heshmati, 2021; Saqib et al., 2023).

Future research should expand the analytical framework to capture dynamic interactions between technological innovation, renewable energy adoption, and environmental quality in SSA. Incorporating panel data techniques that account for structural breaks and cross-sectional dependence, as suggested by Ditzen et al. (2021) and Pesaran (2021), could enhance the robustness of causal inferences. Additionally, the role of financial development and green finance in facilitating clean energy transitions warrants deeper exploration, particularly as SSA economies integrate further into global markets (Fan et al., 2025; Ganda, 2024). Comparative studies across regions with varying income levels could elucidate threshold effects consistent with EKC theory and reveal how structural transformation mediates the energy–growth–environment nexus (Ansari et al., 2020; Alakbarov et al., 2025). Finally, incorporating machine learning and predictive analytics could improve the identification of non-linear relationships and policy-sensitive interventions, enabling evidence-based strategies for sustainable economic growth that simultaneously safeguard ecological integrity.

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