DETERMINANTS OF GREEN GROWTH IN SUB-SAHARAN AFRICA: A Quantile Regression Analysis of Renewable Energy, FDI, and Urbanization

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ABSTRACT

This study investigates the determinants of green growth (GG) in 14 sub-Saharan African countries from 1990 to 2020, focusing on renewable energy consumption, foreign direct investment (FDI), urbanization, population size, GDP per capita, and forest area. Using a range of econometric techniques, including pooled OLS, fixed effects, LSDVs, Driscoll-Kraay standard errors, and Method of Moments Quantile Regression (MM-QR), the study captures both the average and distributional effects of these factors on GG, proxied by energy-related CO_2 emissions per capita. The findings indicate that renewable energy consumption is positively associated with emissions, reflecting transitional energy systems where clean energy complements rather than substitutes for fossil fuel use. Foreign direct investment tends to reduce emissions, particularly in higher emission contexts, suggesting that green investment plays a key role in mitigation. Urbanization and population show mixed impacts, while GDP per capita consistently correlates with higher emissions, underscoring the growth–environment trade-off. Forest cover significantly mitigated emissions across all quantiles. This study calls for integrated policies that expand renewable infrastructure, attract green FDI, and prioritize forest conservation and sustainable urban planning.

Keywords: Green Growth, sub-Saharan Africa, Renewable Energy, Foreign Direct Investment, Urbanization, GDP per capita, Forest conservation

JEL classification: Q56, Q43, F21, O13

1. Introduction

Green growth (GG) has gained increasing attention as a strategy for achieving sustainable development, particularly in sub-Saharan Africa (SSA), a region facing persistent challenges from climate change, energy poverty, and rapid urbanization (Odugbesan et al., 2021; Wang et al., 2023). The aim of GG is to balance economic growth with environmental preservation by reducing carbon emissions and improving resource efficiency. This study investigated the roles of renewable energy consumption, foreign direct investment (FDI), urbanization, population growth, GDP per capita, and forest area in shaping GG across 14 SSA countries from 1990 to 2020.

Despite growing attention to sustainable development in SSA, empirical research continues to provide incomplete understanding of the drivers and complexities underlying GG in the region. Existing studies have explored various dimensions, such as urbanization, energy use, and pollution control. For example, Ibekilo et al. (2023) employed a dynamic panel model to assess how urbanization and energy consumption influence environmental pollution across African economies, uncovering significant cross-country heterogeneity. However, their reliance on mean-based estimation techniques limits insight into how these relationships vary across the distribution of emissions, which is a crucial aspect of targeted policymaking.

Similarly, Emmanuel et al., (2024) examined the fiscal implications of low-carbon energy transitions in oil-dependent African nations, highlighting the important trade-offs in government revenue structures. While their findings are relevant to fiscal policy, this study does not directly engage with environmental or social performance indicators, and its scope is confined to a subset of SSA countries. These limitations reinforce the need for a broader, regionally inclusive, and distribution-sensitive analysis of GG, which captures both environmental outcomes and macroeconomic diversity across SSA.

This study was motivated by the urgent need to address the three interrelated gaps in the GG literature. First, SSA's persistent reliance on fossil fuels and limited renewable energy deployment necessitates deeper empirical investigation into the environmental benefits of renewable energy integration (Shahbaz et al., 2019; Tawiah et al., 2021). Second, the rising inflow of foreign direct investment (FDI) poses both environmental risks and opportunities; however, its differentiated impact across emission intensities remains underexplored (Demena & Afesorgbor, 2020; Tamazian & Rao, 2010). Third, rapid urbanization continues to reshape ecological dynamics in SSA, but its variable effects on emission intensity require further scrutiny (Sarkodie & Adams, 2018; Yasmeen et al., 2020).

Addressing these challenges using a quantile-based econometric approach enables a more nuanced understanding of how these determinants influence environmental outcomes across different levels of carbon intensity. This is essential for designing differentiated evidence-based strategies to advance green growth across SSA's diverse economic and institutional landscapes.

Green growth emphasizes economic expansion without compromising environmental health, a crucial concept for sub-Saharan Africa, which faces rapid population growth, urbanization, agriculture (Wang et al., 2023), and economic pressures that impact sustainability. Theoretical underpinnings suggest substantial economic growth while preserving natural resources and environmental services (Odugbesan et al., 2021; Stern, 2004). However, its practical implementation in sub-Saharan Africa is challenging because of fossil fuel reliance, limited renewable energy infrastructure, and varying institutional qualities.

Despite the potential of renewable energy to foster green growth, empirical evidence shows that it can either enhance or hinder sustainable development, depending on its integration into the energy mix (Tawiah et al., 2021; Yang et al., 2021). Similarly, FDI influence is complex; it can drive technological advancements and improve environmental regulations but can also increase pollution if not properly managed (Demena & Afesorgbor, 2020). The relationship between population dynamics and sustainability is also intricate, with larger populations potentially increasing environmental pressure but offering economies of scale and improved resource utilization (Aller et al., 2015).

Given these complexities, the research problem centres on understanding the multifaceted impacts of economic and demographic factors on green growth in sub-Saharan Africa. This study seeks to dissect these relationships using advanced econometric methods to provide a detailed analysis that can guide effective policymaking. Addressing this problem is crucial for developing strategies that promote sustainable development, while balancing economic growth and environmental conservation.

While numerous studies have investigated the individual effects of renewable energy (Ahmed et al., 2022; Omri et al., 2015), FDI (Demena & Afesorgbor, 2020; Shahbaz et al., 2019), and urbanization (Sarkodie & Adams, 2018) on environmental outcomes, few have comprehensively examined their combined effects on GG, particularly in the SSA context. The unique socio-economic and environmental conditions in SSA, marked by rapid urbanization, institutional fragility, and resource dependency, necessitate a contextualized analysis that integrates multiple dimensions of development.

Moreover, existing literature often overlooks how these variables influence CO_2 emissions across different distribution levels, which is critical for policy differentiation. This study bridges this gap by selecting six key factors: renewable energy, FDI, urbanization, population size, GDP per capita, and forest area, based on their theoretical and empirical relevance to GG (Aller et al., 2015; Barbier, 2010; Odugbesan et al., 2021). The use of the Method of Moments Quantile Regression further enables us to capture heterogeneous effects across emission intensities, offering a nuanced understanding that has not been addressed in previous studies (Ike et al., 2020; Machado & Silva, 2019).

The primary objective of this study is to investigate the relationships between renewable energy consumption, foreign direct investment, urbanization, population size, GDP per capita, and forest area, and their combined effects on green growth. This study sought to answer the following questions.

- How do renewable energy consumption and foreign direct investment influence green growth in sub-Saharan Africa?
- What roles do urbanization, population dynamics, GDP per capita, and forest area play in shaping green growth?
- How do these relationships vary across CO_2 intensity levels, providing a comprehensive understanding of their distributional effects?

The significance of this study lies in its detailed quantile-based analysis that captures the diverse impacts of variables across emission levels. Using the Method of Moments Quantile Regression (MM-QR), it explores the multifaceted influences on green growth, providing insights beyond the average effects that are particularly relevant in sub-Saharan Africa's varied contexts.

This study contributes to the literature on GG and environmental economics in three ways. First, it employs the Method of Moments Quantile Regression (MM-QR) to explore how macroeconomic and environmental factors influence CO_2 emissions across a conditional distribution, offering distribution-sensitive insights often ignored in mean-based estimations. Second, it introduces an interaction term between FDI and urbanization, two critical but interdependent factors in SSA, to uncover potential moderating effects on environmental quality–a relationship rarely examined in prior SSA-focused studies. Third, it builds on a panel dataset covering 14 SSA countries from 1990 to 2020, offering context-specific, policy-relevant evidence that can inform regionally-tailored strategies to achieve green growth under institutional and energy constraints.

Based on these contributions, this study seeks to offer actionable insights for policymakers aiming to balance economic expansion with environmental sustainability. This highlights the imperative for integrated policy frameworks that leverage the synergies between renewable energy adoption, sustainable urban planning, and environmentally-responsible FDI. Additionally, it underscores the roles of forest conservation, education, and targeted economic incentives as complementary instruments to accelerate the region's transition toward low-carbon development pathways and reduce CO_2 emissions.

2. Literature Review

Green growth is a paradigm that integrates both economic and environmental sustainability (Baumgartner, 2019). It hinges on the notion that it is feasible to achieve substantial economic growth while simultaneously ensuring that natural assets continue to provide resources and environmental services on which well-being relies. This approach is encapsulated by the positive impacts of foreign direct investment (FDI) in regions that embrace green growth strategies, where FDI is channelled towards enhancing technological advancements and environmental regulations. Such measures not only improve economic efficiency but also encourage environmentally friendly industrial practices (Odugbesan et al., 2021).

However, in sub-Saharan Africa, studies show that while hydroelectric power remains the dominant renewable source, the adoption of non-hydro renewables is slow (Olanrele & Fuinhas, 2024). Moreover, both FDI and financial development have been found to negatively impact renewable electricity adoption, indicating that these factors do not currently expand renewable electricity generation in the region (Al-Mulali & Tang, 2013; Demena & Afesorgbor, 2020; Tang, 2015).

Feasible strategies for increasing non-hydro renewable electricity use include activating renewable energy support mechanisms and strengthening legal and institutional frameworks to reduce investment bottlenecks and bureaucracies. Recent studies also highlight that urban energy transitions, when supported by equitable green energy access and regulatory frameworks, can substantially reduce pollution and enhance sustainability outcomes in African cities (Mesagan et al., 2024).

Literature underscores the dual role of renewable energy in fostering green growth (Ahmed et al., 2022; Omri et al., 2015; Zameer & Wang, 2018). By innovating renewable energy technologies, countries can induce *green productivity* (Yan et al., 2020) which involves enhancing the efficiency and effectiveness of harnessing natural resources for production and consumption, ultimately leading to sustainable economic development (Tawiah et al., 2021; Waheed et al., 2018; Yan et al., 2020). The international focus on mitigating carbon emissions (Alam et al., 2016; Shahbaz et al., 2019; Yan et al., 2020), as evidenced by the Paris Agreement, further exemplifies the global commitment to transition towards a greener economy (Yasmeen et al., 2020).

The role of population dynamics in the discourse on green growth is significant. Large populations can exert considerable pressure on the environment, potentially hindering green plant growth. However, this relationship is complex and varies by region, necessitating detailed approaches to managing the environmental impacts in densely populated areas (Aller et al., 2015). Thus, green growth strategies must consider demographic factors to achieve sustainable development effectively.

Empirical evidence underscores the significant influence of institutional quality on green economic growth, highlighting that governance structures shape both environmental and economic outcomes (Degbedji et al., 2024). For instance, Nwani et al. (2022) found that good governance fosters green growth in the West African Economic and Monetary Union (WAEMU), with positive effects observed in Côte d'Ivoire and Senegal. However, the impact was weaker or negative in Benin and Burkina Faso, which is attributed to institutional deficiencies. These findings are consistent with those of Zheng et al. (2024), who emphasize the pivotal role of robust institutions in enabling sustainable economic practices, particularly in the context of South Asia.

Furthermore, the impact of financial development on environmental outcomes is intricately linked to institutional quality. These findings are consistent with broader research suggesting that financial development, when coupled with strong institutions, can lead to better environmental and economic outcomes (Li, Wang, & Zhao, 2016).

Trade openness also plays a critical role in shaping green economic growth with complex outcomes that depend heavily on the nature of traded goods and the regulatory environment. Degbedji et al. (2024) discussed how trade policies that encourage the import of renewable technologies can enhance green growth, whereas imports centred on fossil fuel technologies might exacerbate environmental degradation. This dual nature of trade impacts highlights the importance of tailored trade policies that prioritize environmental sustainability and economic goals.

Overall, empirical literature suggests a complex interplay between institutional quality, financial development, and trade policies in influencing green economic growth. Robust institutions appear to enhance the positive impacts of financial development and trade on the environment, highlighting the need for integrated policy frameworks that foster both economic dynamics and environmental sustainability. These insights are crucial for policymakers to develop strategies that harness the benefits of economic openness, while safeguarding environmental integrity.

Thus, current research on green growth (GG) often overlooks the varied impacts of factors such as renewable energy and foreign direct investment across different levels of CO_2 intensity, particularly in sub-Saharan Africa. There is also a lack of comprehensive analysis on how urbanization, population dynamics, GDP per capita, and forest area simultaneously influence GG. This study seeks to address these gaps by employing moments quantile regression (MM-QR) to explore these relationships in detail. This approach provides deeper insight into the specific needs and strategies suitable for enhancing GG in the diverse contexts of sub-Saharan African nations.

Such contextualized approaches are vital, as recent evidence shows that the environmental impact of urban energy strategies is highly dependent on the level of access to clean technologies and the effectiveness of pollution control policies (Mesagan et al., 2024).

3. Data and Methodology

This study uses a strongly balanced panel dataset of seven variables across 14 sub-Saharan African countries from 1990 to 2020. The included countries are Angola, Botswana, Cameroon, Congo, Equatorial Guinea, Ethiopia, Ghana, Kenya, Mozambique, Namibia, Rwanda, Tanzania, Uganda, and Zambia. These countries and the timeframe were chosen based on the availability of valid data and observations for reliable analysis. We employed Stata 18 (StataCorp, 2023) for data analysis and Python (Van Rossum & Drake, 1995) to generate high-quality visualizations.

The variables are sourced from the World Bank's World Development Indicators (WDI) (World Bank, 2024). The outcome variable, representing green growth (GG), is energy-related CO_2 emissions per capita. The primary explanatory variables include renewable energy consumption (RE), foreign direct investment (FDI), urbanization (URB), total population (POP), GDP per capita (GDP), and forest area (FOR). To normalize the data, we applied the natural logarithm (ln) to all variables. These variables were selected to evaluate their impact on the GG. Renewable energy consumption is expected to reduce CO2 emissions and improve environmental outcomes (Shahbaz et al., 2019; Tawiah et al., 2021).

In this study, CO_2 emissions per capita, which served as a partial indicator of GG, were used as a proxy for environmental degradation. Although GG is inherently multidimensional, encompassing environmental sustainability, economic performance, and social inclusion, the use of CO_2 per capita is widely adopted in the empirical literature as a practical proxy for environmental pressure, especially in long-term, cross-country analyses (Emonena & Osifo, 2024; Shahbaz et al., 2019). This choice is particularly relevant in the SSA context, where consistent and comprehensive data on composite GG indicators remain limited.

While the Green Growth Index (GGI) developed by the Global Green Growth Institute offers a more holistic metric, its availability is restricted to more recent years and lacks the historical depth (1990–2020) required for this panel study. Moreover, the GGI is not yet fully accessible across all SSA countries, limiting its utility in econometric modelling at the regional level. As such, CO_2 emissions per capita were retained as a feasible and policy-relevant proxy for examining the environmental dimension of GG in SSA.

Correspondingly, foreign direct investment is expected to have a mixed effect, potentially increasing emissions through industrial activities but promoting cleaner technologies (Demena & Afesorgbor, 2020; Khan et al., 2020). Urbanization is likely to increase CO_2 emissions owing to industrial activities in urban areas (Aller et al., 2015; Sarkodie & Adams, 2018). The total population has a complex relationship with CO_2 emissions, balancing higher resource demand and scale efficiency (Aller et al., 2015; Parajuli et al., 2019). The GDP per capita is expected to correlate positively with CO_2 emissions because of higher economic activity (Degbedji et al., 2024; Orhan et al., 2021). Forested areas are expected to reduce CO_2 emissions by acting as carbon sinks (Barbier, 2010; Bhattarai & Hammig, 2001).

Using both the urban population and total population as explanatory variables is justified by their distinct yet interrelated impacts on CO_2 emissions. The urban population (URB) captures the effects of urbanization, such as increased industrial activity and transportation emissions (Aller et al., 2015; Sarkodie & Adams, 2018). The total population (POP) encompasses the overall demographic pressure on resources and emissions (Alam et al., 2016; Parajuli et al. 2019). Including both variables disentangles urbanization's specific contributions from general population growth, providing a comprehensive analysis of their impacts on green growth.

As robustness checks, this study applies the Pedroni Test for Panel Cointegration to confirm the long-term equilibrium relationship among the variables (Pesaran, Shin, & Smith, 2001). This test ensures that the variables are cointegrated, indicating that a stable long-term relationship is essential for policy recommendations. Various panel regressions are employed, including OLS Pooled, Random Effects, and Fixed Effects models, to account for unobserved heterogeneity and control for individual country differences (Li et al., 2016). Least Squares Dummy Variables (LSDVs) and Driscoll-Kraay Standard Errors were used to address potential heteroscedasticity and cross-sectional dependence, ensuring robust and reliable estimates.

The primary analytical approach is the Method of Moments Quantile Regression (MM-QR), which is applied to the 10^{th} through the 90^{th} quantiles. This method provides a comprehensive understanding of the conditional distribution of GG across different quantiles and offers detailed insights into the dynamics of the dependent variable at various levels (Machado and Silva, 2019). The MM-QR approach is particularly pertinent for capturing the heterogeneous effects of the explanatory variables across different emission levels, reflecting the diverse economic and environmental contexts of the studied countries. This method allows for a more detailed analysis than the traditional mean regression techniques, which is critical for understanding the varying impacts of factors such as FDI and renewable energy consumption at different levels of CO_2 emissions.

Table 1 summarizes the variables' descriptions, sources, and a priori expectations, providing a clear framework for the analysis and ensuring consistency with the theoretical underpinnings discussed in the literature review.

Table 1: Data Sources and Variables Descriptions

Variable	Description	Signs	Sources
GG	Green Growth: Production-based CO2 intensity,	Negative (-)	OECD
RE	Renewable energy consumption (% of total final energy consumption)	Positive (+)	WDI
FDI	Net inflow of foreign direct investment as % of GDP	Positive (+)	WDI
URB	Urban population (% of total population)	Mixed (+/-)	WDI
POP	Log of the total population	Mixed (+/-)	WDI
GDP	GDP per capita (constant 2015 US$)	Positive (+)	WDI
FOR	Forest area (% of total land area)	Positive (+)	WDI

Source: Authors' compilations

3.1 Conceptual framework and econometric model

This study aligns with a theoretical framework that explores the relationship between economic variables and environmental sustainability. Specifically, it builds upon theories positing a link between renewable energy consumption, foreign direct investment, urbanization, population growth, economic performance, and forest conservation and their combined effects on CO_2 intensity (Omri et al., 2015; Sadorsky, 2009; Shahbaz et al., 2019; Waheed et al., 2018).

According to these theories, renewable energy usage can mitigate CO2 emissions, while urbanization and population growth can either exacerbate or alleviate these emissions, depending on various factors, such as technological advancements and policy implementation. Economic performance, often measured by GDP per capita, can influence CO2 emissions through increased production and consumption activities, whereas forest conservation is expected to reduce CO2 emissions by enhancing carbon sequestration.

To address these suppositions, this study primarily utilized the Mixed-Model Quantile Regression (MM-QR) method as the ultimate analytical approach. Additionally, panel regressions (Pooled, Random Effects, and Fixed Effects), Least Squares Dummy Variable (LSDV) models, and Riscoll-Kraay standard errors were employed as robustness checks.

The empirical model used in this study is as follows:

$$\boldsymbol{ln}\ (\boldsymbol{GG}_{\mathbf{it}}) = \beta_0 + \beta_1 ln(RE_{it}) + \beta_2 ln(FDI_{it}) + \ \beta_3 ln(URB_{it}) + \beta_4 ln(POP_{it}) + \ \beta_5 ln(GDP_{it}) + \ \beta_6 ln(FOR_{it}) + \gamma_t + \epsilon_{it} \quad (1)$$

where:

$\boldsymbol{GG}_{\mathbf{it}}$ is the production-based CO2 intensity, represents green growth,

$ln(RE_{it})$ is the natural logarithm of renewable energy consumption as a percentage of total final energy consumption (representing green growth),

$ln(FDI_{it})$ is the natural logarithm of the net inflow of foreign direct investment as a percentage of GDP,

$ln(URB_{it})$ is the natural logarithm of the urban population as a percentage of the total population,

$ln(POP_{it})$ is the natural logarithm of the total population,

$ln(GDP_{it})$ is the natural logarithm of GDP per capita (constant 2015 US$),

$ln(FOR_{it})$ is the natural logarithm of forest area as a percentage of total land area,

γ_t represents year dummies to control for yearly variations and common shocks, and

ϵ_{it} is the general error term.

Based on theoretical expectations, β_1 is expected to be negative, indicating that higher renewable energy consumption reduces the CO2 intensity. β_2 is expected to be positive, suggesting that increased foreign direct investment may lead to a higher CO2 intensity due to industrial activities. β_3 and β_4 have mixed expectations because urbanization and population growth can have both positive and negative effects on CO2 intensity. β_5 is expected to be positive, indicating that higher GDP per capita can lead to higher CO2 intensity. β_6 is expected to be negative, suggesting that a greater forest area contributes to lower CO2 intensity.

By employing MM-QR regression as the primary method and utilizing various robustness checks, this study aims to provide comprehensive insights into the complex dynamics between these variables and CO2 intensity. Robustness analyses ensured the reliability and consistency of the results, offering a thorough understanding of the environmental impacts of these economic and demographic factors.

Note that based on the expectation that $\beta_1 < 0$ and $\beta_6 < 0$, the sign of the coefficient of the interaction term β_3 gauges if the interaction of urban population and foreign direct investment boosts or alters the impact on CO2 intensity. A positive (negative) sign of the interaction coefficient shows that urbanization and foreign direct investment together increase (decrease) CO2 intensity. Therefore, the total effect of urban population on CO2 intensity given foreign direct investment is computed as:

$$\frac{\partial \ln (GG)}{\partial \ln (URB)} = \beta_3 + \beta_2 \ln (FDI) \quad (2)$$

If $\beta_2 > 0$, it implies that foreign direct investment enhances the impact of the urban population on CO2 intensity. However, if $\beta_1 < 0$, the overall impact of urban population on CO2 intensity depends on the magnitude of the negative sign. If the negative sign of β_2 outweighs the positive sign of β_3, then foreign direct investment mitigates the impact of urban population on CO2 intensity. Conversely, if the negative sign of β_2 is less than the positive sign of β_3, this suggests that the mitigating effect of foreign direct investment is not sufficient to constrain the positive effect of urban population on CO2 intensity. Finally, if $\beta_2 = 0$, it indicates that the interaction of foreign direct investment with the urban population has no significant impact on CO2 intensity.

So, if $\beta_3 > 0$, it implies that foreign direct investment enhances the impact of the urban population on CO2 intensity. However, if $\beta_3 < 0$, the overall impact of urban population on CO2 intensity depends on the magnitude of the negative effect. If the negative sign of β_3 outweighs the positive sign of β_1, then foreign direct investment mitigates the impact on the urban population. Conversely, if the negative sign of β_3 is less than the positive sign of β_1, then the mitigating effect is insufficient to constrain the positive impact. Finally, if $\beta_3 = 0$, this indicates that the interaction of foreign direct investment with urban areas has no significant impact on CO2 intensity.

3.2 Estimation techniques and approach

To highlight the significance of economic variables on energy-related CO2 emissions per capita (Green Growth, GG), this study employed several estimation techniques. Initially, the Pedroni Test for Panel Cointegration was used to examine the long-run relationship between variables. Following this, the study used panel regressions (Ordinary Least Squares Pooled, Random Effects, and Fixed Effects), Least Squares Dummy Variables (LSDVs), and Driscoll-Kraay Standard Errors (SE) for robustness checks. These methods ensure that the results are robust, and account for potential cross-sectional dependence and endogeneity.

According to Torres-Reyna (2007), the LSDV model is effective for understanding fixed effects. This technique allows the effects of renewable energy consumption, foreign direct investment, urban population, population growth, GDP per capita, and forest area to be mediated by differences across cross-sectional units using dummy variables. The pure impact of each variable was estimated by adding a dummy for each cross-section while controlling for unobserved heterogeneity. Essentially, each dummy absorbs the effects particular to each subsample.

For the main analysis, this study employs the Method of Moments Quantile Regression (MM-QR) developed by Machado and Silva (2019). This approach is robust for handling fixed effects in panel quantile models and allows for the estimation of other aspects of the conditional distribution of the dependent variable, GG, at various quantiles (10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th). Modifying the initial equation and following Machado and Silva (2019) and Ike et al. (2020), the conditional quantile Q_{GG} $(\tau|X)$ estimation takes the following general specifications:

$$\boldsymbol{Q_{GG}\ (\tau|X) = \ (\alpha_i + \delta_i q(\tau)) + X'_{it}\beta + Z'_{it}\gamma q\ (\tau)} \tag{3}$$

where:

$\boldsymbol{X'_{it}}$ is a vector of all explanatory variables used in the study;

$\boldsymbol{Q_{GG}\ (\tau|X)}$ represents the quantile distribution of the dependent variable conditional on the location of explanatory variables;

$\boldsymbol{\alpha_i(\tau) = \ \alpha_i + \delta_i q(\tau)}$ is the scalar coefficient of the quantile -τ fixed effect for individual i; and

Z' is a k-vector of known differentiable transformations of the components of X with element l where l=1,…, k, and q (τ) is the τ-th quantile derived from the following optimization function:

$$min_q \ \Sigma_i \Sigma_\tau \rho \ (\mathrm{R}_{it} - \ (\delta_i + \boldsymbol{Z}'_{it}\boldsymbol{\gamma})\boldsymbol{q}) \tag{4}$$

where: ρ_τ (A) = $(\tau - 1)$ A II {A < 0} + τ A II {A < 0} denotes the check function.

The MM-QR technique was utilized as the main analytical method, ensuring the robustness and consistency of the main regressors' impacts on energy-related CO2 emissions per capita (GG) across different quantiles. The panel cointegration test and various panel regression models served as robustness checks to validate the quantile regression analysis findings.

4. Findings and Discussion

4.1 Descriptive statistics and correlation analysis

The summary statistics in Table 2 offer insights into the central tendencies and variability of the key variables. The average energy-related CO_2 emissions per capita (GG) is 2.5432, with renewable energy consumption (RE) at 4.1924% and foreign direct investment (FDI) at 1.2933% of GDP. The average urban population (URB) was 3.5052%, whereas the total population logarithm (POP) was 16.4410. The average GDP per capita (GDP) is 7.1349, and the forest area percentage (FOR) is 3.4568%. The standard deviations indicate that FDI has the highest variability (0.8719), and GG has the lowest (0.4173), suggesting a transitional phase in energy use, aligned with Degbedji et al. (2024). The correlation matrix shows significant relationships: GG positively correlates with RE (0.5934) and POP (0.5673), but negatively correlates with URB (-0.5049) and GDP (-0.4532). This suggests that higher renewable energy consumption and larger populations increase CO2 emissions, while higher urbanization and GDP reduce them, supporting the findings of Ahmed et al.(2022).

Finally, the strong negative correlation between RE and GDP (-0.7746) reflects the concerns highlighted by Li et al. (2016) who emphasized the need for policies that support both economic growth and environmental sustainability. Strengthening the role of renewable energy is crucial for reducing fossil fuel dependency and promoting a greener economy in sub-Saharan Africa.

Table 2: Summary Statistics and Correlation Results

Item	GG	RE	FDI	URB	POP	GDP	FOR
Mean	2.5432	4.1924	1.2933	3.5052	16.4410	7.1349	3.4568
Std. dev.	0.4173	0.5783	0.8719	0.4858	1.3295	0.9512	0.7744
Min	1.6174	1.5433	-2.4799	1.8588	13.0510	5.2541	1.9726
Max	3.6022	4.5985	5.0927	4.3054	18.5793	9.5627	4.5770
Observations	434	434	434	434	434	434	434
Correlation Matrix							
GG	1.0000						
RE	0.5934	1.0000					
FDI	-0.191	-0.1486	1.0000				
URB	-0.5049	-0.554	0.2831	1.0000			
POP	0.5673	0.6825	-0.2241	-0.3879	1.0000		
GDP	-0.4532	-0.7746	0.1256	0.7547	-0.5389	1.0000	
FOR	-0.0909	-0.1019	0.3052	0.5632	-0.0854	0.156	1.0000

Source: Authors' compilations

Table 3 presents the results of the Pesaran et al. (2004) CD test conducted on the residuals of the fixed effects model. The test statistic (–0.668) and the corresponding p-value (0.5043) indicate no significant cross-sectional dependence among the panel units. This finding suggests that the cross-country error structure does not violate the assumption of independence, thus validating the reliability of the panel estimators used.

While the study employs robust estimators, such as MMQR and Driscoll–Kraay standard errors, which can account for CD, this diagnostic confirms their appropriateness and further strengthens the robustness of the empirical results.

Table 3: Cross-Sectional Dependence Test Result

Test	Statistic	p-value	Conclusion
Pesaran CD test (fixed effects residuals)	–0.668	0.5043	No cross-sectional dependence

4.2 Empirical findings

This section presents empirical findings on the relationships between economic variables and energy-related CO2 emissions per capita in sub-Saharan Africa. It includes panel cointegration tests, panel regression models (Pooled, Random Effects, Fixed Effects), and results from LSDVs and Driscoll-Kraay standard errors to ensure robustness and reliability.

The results of the Pedroni test for cointegration, as presented in Table 4, indicate the rejection of the null hypothesis of no cointegration among the variables. Specifically, the Modified Phillips–Perron t-statistic (2.1979, p-value = 0.0140), Phillips–Perron t-statistic (-4.0907, p-value = 0.0000), and Augmented Dickey-Fuller t-statistic (-3.6415, p-value = 0.0001) suggest significant cointegration at conventional levels. This implies that the variables share a long-term equilibrium relationship across the 14 sub-Saharan African countries over the 30 years studied.

Table 4: Panel Cointegration tests

Pedroni Test for Cointegration		
H_0: No cointegration	Number of panels = 14	
H_a: All panels are cointegrated.	Number of periods = 30	
Cointegrating vector: Panel specific		
Panel means: Included	Kernel: Bartlett	
Time trend: Not included	Lags: 3.00 (Newey–West)	
AR parameter: Panel specific	Augmented lags:1	
	Statistic	p-value
Modified Phillips–Perron t	2.1979	0.0140
Phillips–Perron t	-4.0907	0.0000
Augmented Dickey-Fuller t	-3.6415	0.0001

Source: Authors' compilations

4.2.1 *Panel Regressions, LSDVs, and Driscoll-Kraay SE Results*

Table 5 presents the results of multiple panel estimators, including Pooled OLS, Random Effects (RE), Fixed Effects (FE), Least Squares Dummy Variables (LSDVs), and Driscoll–Kraay standard errors (DKSE), that examine the drivers of environmental performance in sub-Saharan Africa (SSA), using CO_2 emissions per capita as a proxy for environmental pressure and, by extension, Green Growth (GG).

A key finding is that renewable energy consumption (lnRE) was consistently associated with higher CO_2 emissions across all models, with statistically significant and positive coefficients (for example, 0.647 for FE, 0.594 for LSDVs, and 0.319 for DKSE). This counterintuitive result suggests that, in SSA, the current scale or structure of renewable energy deployment may not be sufficient to offset emissions from fossil fuel use. This aligns with the arguments of Ibekilo et al. (2023) that transitional energy systems often coexist with carbon-intensive sources during the early renewable adoption phases.

Table 5: Panel Regressions, LSDVs, and Driscoll-Kraay SE Results

Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)
	Pooled	Random Effects	Fixed Effects	LSDVs	Driscoll-Kraay SE
lnRE	0.6157825***	0.6157825***	0.6473303***	0.5936139***	0.3191305***
	(0.0498098)	(0.0498098)	(0.0502515)	(0.0491627)	(0.0945386)
lnFDI	-0.042152***	-0.042152***	-0.0246595*	-0.0770268***	-0.0064277
	(0.0153578)	(0.0153578)	(0.0149227)	(0.0157868)	(0.0299442)
lnURB	-0.551181***	-0.551181***	0.1676344	-0.3271093**	-0.6372908***
	(0.0813754)	(0.0813754)	(0.1241742)	(0.1320772)	(0.1008883)
lnPOP	-0.0105078	-0.0105078	-.2812968***	-1.360842***	0.0964758**
	(0.0418279)	(0.0418279)	(0.0816723)	(0.1850965)	(0.0362069)
lnGDP	0.5260801***	.05260801***	0.5836862***	0.609674***	0.2490299***
	(0.0428911)	(0.0428911)	(0.0416915)	(0.0401033)	(0.0796696)
lnFOR	0.2139264**	0.2139264**	1.532644***	1.837821***	0.1691288***
	(0.0914082)	(0.0914082)	(0.3356309)	(0.3365128)	(0.055863)
Cons	-2.372214***	-2.372214***	-5.564196**	11.40877***	-0.5002418
	(0.8918734)	(0.8918734)	(2.276104)	(3.55635)	(1.197551)
			51.39 [0.0000]		
Nº of Obs.	420	420	420	434	420
Number of groups	14	14	14	14	14
R^2	0.3509	0.3509	0.4175	0.8405	0.5282
F-Stat./ Wald chi^2	219.16***	219.16***	49.46***	41.29***	690.00***

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are shown in parentheses.
Source: Authors' computation

Similarly, foreign direct investment (lnFDI) showed a negative effect in most models (significant in Pooled, RE, and LSDVs), supporting the idea that targeted FDI can reduce emissions through cleaner technologies and knowledge spillovers, consistent with Tamazian and Rao (2010) and Demena and Afesorgbor (2020).

Urbanization (lnURB) had mixed effects: significantly negative in the Pooled, LSDVs, and DKSE models, but insignificant and even positive in the FE model. This inconsistency may reflect differences in urban planning quality across SSA countries. Yasmeen et al. (2020) suggest that well-managed urbanization can reduce emissions, while poorly planned growth exacerbates environmental stress.

GDP per capita (lnGDP) consistently showed a positive and significant association with CO_2 emissions, indicating that economic growth continues to exert upward pressure on emissions, highlighting the classic growth-environment trade-off emphasized by Stern (2004).

Forest area (lnFOR) was positively associated with GG across all models. While this may seem unexpected, it likely reflects the absorptive role of forests in carbon sinks as well as the economic contributions of forest-based sectors. Similar results were obtained by Odugbesan et al. (2021).

The Driscoll–Kraay model, which adjusts for potential cross-sectional dependence, yielded lower coefficient magnitudes and changes in statistical significance for some variables (for example, FDI became insignificant), but retained the key patterns. These differences underscore the need for robust estimation techniques to provide accurate policy insight.

In summary, the findings from Table 5 emphasize that current renewable energy systems in SSA may not yet be strong enough to deliver emission reductions, highlighting the need for structural improvements in energy policy. Moreover, economic growth and urbanization require targeted green interventions to decouple emissions. These results serve as a robust foundation for a more granular quantile-based analysis, as discussed in the subsequent section.

4.2.2 *Quantile Impacts from MM-QR Analysis*

Table 6 presents the results of the Method of Moments Quantile Regression (MM-QR), which estimates the heterogeneous effects of economic and environmental variables on CO_2 emissions per capita, a proxy for environmental performance, in SSA. Unlike traditional regressions, the quantile approach allows us to examine how these effects vary across emission distributions, offering deeper insights into the dynamics of GG under different levels of environmental stress.

The results show that renewable energy consumption (lnRE) is associated with a positive and statistically significant impact on CO_2 emissions across all quantiles, with coefficients declining slightly from 0.632 at the 10th quantile to 0.555 at the 90th quantile. This result, while seemingly counterintuitive, is consistent with the panel regression estimates in Table 5 and suggests that current renewable energy initiatives in SSA may not yet be mature enough to deliver meaningful emission reductions. Instead of displacing fossil fuel use, renewable energy appears to be additive in nature, possibly owing to hybrid energy systems, poor grid integration, or the limited scale of renewables relative to fossil-based baselines.

This transitional pattern aligns with prior findings that green energy access remains insufficient to offset pollution in the short term, particularly in under-resourced urban regions (Mesagan et al., 2024). As Ibekilo et al. (2023) and Wang et al. (2023) suggested, in developing contexts, renewable technologies often coexist with conventional energy sources during the early phases of adoption, leading to parallel consumption rather than substitution.

Therefore, the positive coefficient should not be interpreted as renewable energy causing environmental degradation per se but rather as evidence of the transitionary stage of energy reform in the region. The practical implication is that SSA countries must strengthen their renewable energy infrastructure, expand access to off-grid clean energy, and reduce reliance on conventional fuels to harness the full environmental benefits of renewable energy.

Foreign direct investment (lnFDI) demonstrated a negative and increasingly significant effect across the emission distribution, ranging from –0.050 at the 10th quantile to –0.104 at the 90th quantile. This gradient suggests that, in high-emission contexts, FDI is more effective in reducing environmental pressure, likely through the transfer of cleaner technologies, improved production standards, and stricter environmental oversight tied to foreign capital. This finding reinforces the argument by Tamazian and Rao (2010) and Demena and Afesorgbor (2020) that the environmental impact of FDI is context-dependent, with greater potential for green benefits when host countries have adequate institutional and regulatory capacities. Policymakers in SSA must therefore focus not only on attracting FDI, but also on steering it toward environmentally-responsible sectors, particularly in emission-intensive economies.

The relationship between urbanization (lnURB) and CO_2 emissions is negative and statistically significant in the lower quantiles, with diminishing effects as emissions rise. The coefficient falls from –0.467 at the 10th quantile to –0.187 at the 90th quantile, indicating that in less industrialized countries, early-stage urbanization is associated with higher emissions, likely due to increased construction, traffic congestion, and inefficient energy systems. The negative impact of urbanization in lower quantiles may stem from unplanned urban expansion and inadequate energy systems, as also observed by Mesagan et al. (2024), who emphasized the need for inclusive green energy access during urban transitions.

Table 6: Quantile Impacts from MM-QR Technique

Variable	Qtile_10	Qtile_20	Qtile_30	Qtile_40	Qtile_50	Qtile_60	Qtile_70	Qtile_80	Qtile_90
lnRE	0.632283***	0.6188112***	0.6101512***	0.5996799***	0.591773***	0.5842959***	0.5763261***	0.5643328***	0.5547695***
	(0.102211)	(0.0787355)	(0.0660569)	(0.0553718)	(0.0524773)	(0.0546723)	(0.0617849)	(0.0784491)	(0.0947192)
lnFDI	-0.0498119	-0.0592932**	-0.0653881***	-0.0727576***	-0.0783224***	-0.0835847***	-0.0891938***	-0.0976345***	-0.104365***
	(0.032923)	(0.0253294)	(0.0212798)	(0.017869)	(0.0169245)	(0.0176045)	(0.0199363)	(0.0252501)	(0.0304767)
lnURB	-0.4667725	-0.4181157*	-.3868379**	-0.3490182**	-.3204604**	-0.2934553*	-0.2646701	-0.2213535	-0.1868133
	(0.295659)	(0.2277101)	(0.1910703)	(0.1601963)	(0.1518098)	(0.1581283)	(0.1787504)	(0.2268992)	(0.2739577)
lnPOP	-1.517418***	-1.462869***	-1.427803***	-1.385404***	-1.353388***	-1.323112***	-1.290841***	-1.242279***	-1.203556***
	(0.404032)	(0.3112285)	(0.2610892)	(0.2188387)	(0.2074012)	(0.2160868)	(0.2441927)	(0.3100995)	(0.3744463)
lnGDP	.6412637***	0.6302583***	0.6231837***	0.6146294***	0.6081701***	0.6020619***	0.5955511***	0.5857536***	0.5779411***
	(0.087488)	(0.0673961)	(0.056532)	(0.0473777)	(0.044903)	(0.0467882)	(0.0528681)	(0.0671504)	(0.08109)
lnFOR	1.439745**	1.57843***	1.667579***	1.775375***	1.856772***	1.933744***	2.015789***	2.139252***	2.2377***
	(0.591239)	(0.4551076)	(0.3820303)	(0.3204798)	(0.3036324)	(0.3160949)	(0.3576043)	(0.453588)	(0.5476732)
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	434	434	434	434	434	434	434	434	434

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Standard errors are shown in parentheses.

Source: Authors' computations.

However, the weakening effect at higher quantiles may suggest that larger urban centres benefit from improved infrastructure or economies of scale in emission management. These findings are in line with those of Yasmeen et al. (2020), who highlight the dual role of urbanization in shaping environmental outcomes. This underscores the importance of investing in sustainable urban infrastructure and transport systems, especially in countries undergoing rapid urban expansion.

Population size (lnPOP) exhibited a strong and negative association with GG across all quantiles, suggesting that population growth contributes to higher CO_2 emissions. The coefficients ranged from –1.517 at the 10th quantile to –1.204 at the 90th quantile, reflecting consistent environmental pressure from increasing demographic demand. While large populations can, in theory, enhance resource efficiency through agglomeration effects, inadequate planning, infrastructure deficits, and informal urban settlements limit these benefits in many SSA countries. As Alam et al. (2016) observed, population-driven environmental stress is particularly acute when public services are weak. The practical implication is clear: population growth must be accompanied by strategic urban and environmental planning to mitigate its ecological impacts.

GDP per capita (lnGDP) showed a positive and significant relationship with CO_2 emissions across the quantiles, with the coefficients declining slightly from 0.641 to 0.578. This reinforces the earlier panel regression finding that economic expansion in SSA is currently carbon intensive. According to Stern (2004), developing economies tend to follow a trajectory in which emissions increase with GDP until environmental policies, technological advancement, and structural shifts eventually decouple growth from degradation. However, in SSA, this decoupling has not yet occurred at this scale. Countries must adopt low-carbon development strategies, such as energy efficiency, green industrialization, and climate-resilient infrastructure, to align economic progress with sustainability goals.

Forest area (lnFOR) was positively and significantly associated with improved environmental performance across all quantiles, with coefficients rising from 1.440 to 2.238. This finding confirms the critical role of forests as natural carbon sinks and a buffer against land degradation, aligning with Barbier (2010) and Bhattarai and Hammig (2001). Notably, the impact is stronger in higher-emission contexts, suggesting that forest cover is particularly important when anthropogenic pressure is the greatest. This underscores the importance of forest conservation, reforestation, and sustainable land-use policies in achieving climate goals.

Taken together, the MM-QR findings reinforce the broader results of the panel regressions while adding valuable distributional insights. Renewable energy, though promising, currently exhibits limited effectiveness in mitigating emissions, which calls for deeper reforms and investments. Foreign direct investment has emerged as a potentially powerful tool for emission reduction in high-emission countries, while urbanization and population growth continue to drive environmental stress, especially in less developed settings. The persistent positive link between GDP and emissions underscores the urgency to integrate sustainability into growth models. Forest conservation remains a high-impact strategy across all emission levels.

These findings have significant policy implications. To foster green growth, SSA countries must implement context-sensitive integrated strategies that promote clean energy transitions, regulate FDI quality, plan sustainable urban growth, and expand forest protection. Without such holistic approaches, the region's developmental progress may remain closely tied to rising environmental degradation.

Figure 1 illustrates the quantile-specific impact of the explanatory variables on CO_2 emissions per capita. The positive but slightly declining trend of lnRE confirms its limited but consistent role across the emission spectrum, reflecting early-stage renewable adoption. The foreign direct investment (lnFDI) shows a stronger negative effect at higher quantiles, suggesting its greater environmental benefit in high-emission contexts.

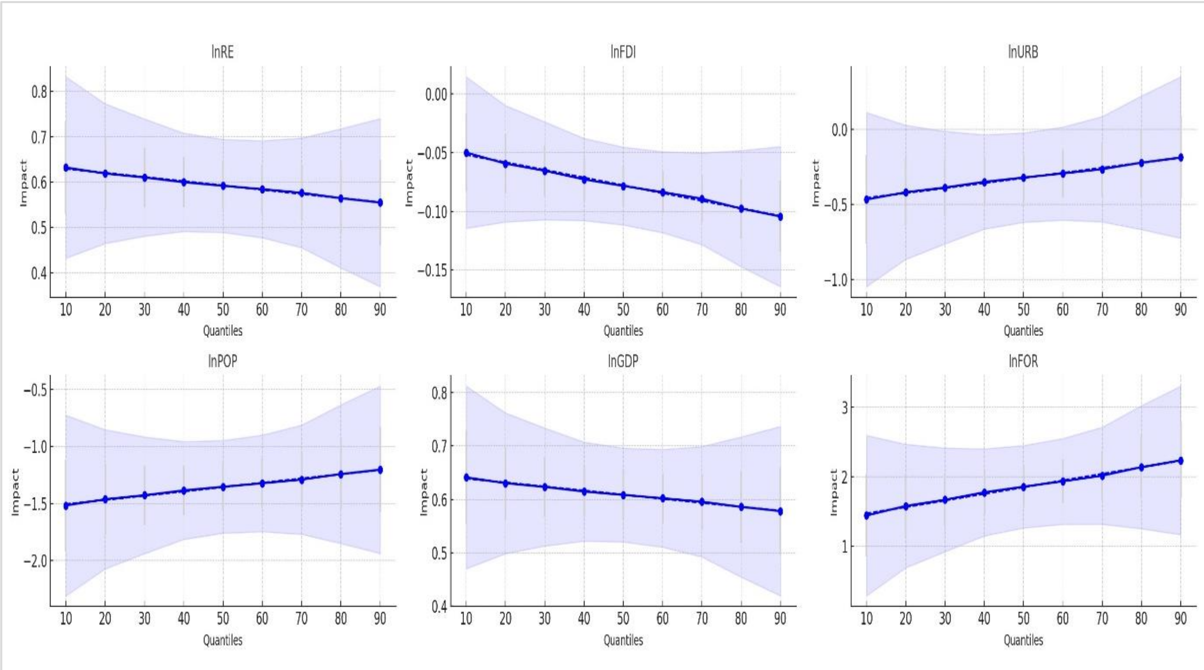

Figure 1: Quantile Impacts from MM-QR Technique

Source: Authors' Creation Using Python.

The urban population (lnURB) had a negative impact that weakened across quantiles, indicating that urbanization pressures are more acute at lower emission levels. lnPOP consistently showed a strong negative impact, highlighting population growth as a major driver of emissions. lnGDP had a positive but flattening trend, reinforcing the growth-emission trade-off. Finally, lnFOR displayed a rising positive impact, confirming the increasing role of forests in mitigating emissions, especially in more polluted environments.

Overall, the figure visually confirms the heterogeneity in variable impacts across different emission intensities, complementing the MM-QR findings.

4.3 Policy implications

The findings from both panel regressions and quantile analysis reveal complex, often counterintuitive, dynamics between economic drivers and environmental performance in sub-Saharan Africa (SSA), particularly regarding CO_2 emissions per capita.

First, the positive and significant coefficients for renewable energy across all estimations suggest that, although renewable energy usage is expanding, it has yet to meaningfully displace fossil fuel-based energy. This finding implies that the renewable energy infrastructure in SSA is still in a transitional phase, possibly operating alongside the existing polluting systems. To address this, SSA governments should prioritize scaling up grid integration, enhancing off-grid renewable access in rural areas, and creating financial incentives for renewable energy adoption. For instance, Rwanda's mini-grid investments in rural electrification offer a replicable model across the region.

Second, foreign direct investment (FDI) demonstrates a robust and increasingly negative impact on emissions across the quantile spectrum, particularly in high-emission contexts. This suggests that foreign capital, when directed toward environmentally-sound sectors, can bring valuable technologies and standards. Therefore, policy frameworks must emphasize not only increasing FDI volumes but also improving their environmental quality. Green investment incentives; environmental screening in investment codes; and Environmental, Social, and Governance (ESG) regulations could ensure alignment between foreign capital and sustainability goals.

Third, the relationship between urbanization and environmental outcomes is unclear. Urbanization is linked to higher emissions at lower quantiles, but its impact weakens at higher quantiles. This indicates that early-stage urban growth is often environmentally damaging, but mature cities may benefit from infrastructure efficiency. To ensure that urban areas become engines of green growth, countries must invest in sustainable public transport, waste management systems, energy-efficient housing, and green urban design. Examples such as Addis Ababa's light rail project can inform similar initiatives for rapidly urbanizing SSA cities.

Fourth, population growth poses consistent environmental pressure across all quantiles. This suggests that demographic expansion in SSA is outpacing infrastructure capacity. While large populations offer potential economies of scale, their benefits are not realized without efficient planning. Policymakers must adopt integrated land-use planning, enhance basic service delivery, and invest in green skills and employment, especially in densely-populated countries, such as Nigeria and Ethiopia.

Fifth, GDP per capita is positively linked with CO_2 emissions, confirming that SSA's growth path is still emission intensive. This underscores the need for structural reforms toward green industrialization and energy efficiency. Programmes such as low-carbon transport systems, clean manufacturing hubs, and carbon pricing mechanisms can help decouple emissions from economic growth.

Finally, forest areas consistently showed a positive effect in reducing emissions, especially in higher-emission settings. This emphasizes the critical role of forest conservation and reforestation in climate change mitigation. Countries such as the Democratic Republic of Congo and Mozambique must strengthen forest governance, curb illegal logging, and link conservation with livelihoods through the REDD+ and agroforestry initiatives.

4.4 Future research agenda and study limitations

While this study offers valuable insights into the economic-environmental nexus in SSA, it is not without limitations. First, the use of CO_2 emissions per capita as a proxy for green growth, although supported by literature, does not fully capture the multidimensional nature of green growth, which includes social, institutional, and innovation-related aspects. Future studies should explore composite indices, such as the Green Growth Index, once more consistent and historical data become available for SSA.

Second, the sample included only 14 countries due to data limitations, which may affect the generalizability of the findings. Expanding the country pool and examining sub-regional heterogeneities (e.g. landlocked vs. coastal and oil-exporting vs. non-oil economies) would yield more tailored policy insights.

Third, this study does not explicitly account for institutional quality, environmental regulation, or energy mix composition, factors that can significantly influence the environmental impacts of growth and investment. Incorporating such variables in future research could enhance our understanding of contextual dynamics and policy effectiveness.

Fourth, while the MM-QR model captures distributional effects, future studies might also consider dynamic quantile models, spatial econometrics, or machine learning approaches to better account for temporal shifts and spatial spillovers.

Finally, qualitative insights on policy implementation, public acceptance of green reforms, and barriers to renewable energy adoption remain underexplored in the empirical literature. Mixed-methods studies combining econometric and field-based approaches could offer a richer picture of the pathways to green growth in SSA.

5. Conclusion

This study examined the nexus between green growth (GG) and economic development in sub-Saharan Africa (SSA) from 1990 to 2020, employing robust econometric methods, including panel regressions and the Method of Moments Quantile Regression (MM-QR). By using CO_2 emissions per capita as a proxy for environmental performance, the analysis revealed the heterogeneous impacts of renewable energy consumption, foreign direct investment, urbanization, population size, GDP per capita, and forest area on GG across emission levels and economic contexts.

The results indicate that, while renewable energy has the potential to contribute to GG, its current scale and integration in SSA do not offset the environmental impacts of fossil fuels. Foreign direct investment has emerged as a beneficial tool in high-emission contexts, suggesting that environmental regulations can mediate its effects. Urbanization and population growth continue to exert environmental pressure, particularly in the lower quantiles of emissions, while economic growth remains positively associated with CO_2 emissions across the board. Forest areas consistently demonstrate a strong positive environmental impact, underscoring their value in climate-mitigation efforts.

References

Ahmed, Z., Ahmad, M., Rjoub, H., Kalugina, O. A., & Hussain, N. (2022). Economic growth, renewable energy consumption, and ecological footprint: Exploring the role of environmental regulations and democracy in sustainable development. *Sustainable Development*, *30*(4), 595–605.

Alam, M. M., Murad, M. W., Noman, A. H. M., & Ozturk, I. (2016). Relationships among carbon emissions, economic growth, energy consumption and population growth: Testing Environmental Kuznets Curve hypothesis for Brazil, China, India and Indonesia. *Ecological Indicators*, *70*, 466–479.

Aller, C., Ductor, L., & Herrerias, M. J. (2015). The world trade network and the environment. *Energy Economics*, *52*, 55–68.

Al-Mulali, U., & Tang, C. F. (2013). Investigating the validity of pollution haven hypothesis in the Gulf Cooperation Council (GCC) countries. *Energy Policy*, *60*, 813–819.

Barbier, E. B. (2010). *A global green new deal: Rethinking the economic recovery*. Cambridge University Press.

Baumgartner, R. J. (2019). Sustainable development goals and the forest sector—A complex relationship. *Forests*, *10*(2), 152.

Bhattarai, M., & Hammig, M. (2001). Institutions and the environmental Kuznets curve for deforestation: A cross country analysis for Latin America, Africa and Asia. *World Development*, *29*(6), 995–1010.

Degbedji, D. F., Akpa, A. F., Chabossou, A. F., & Osabohien, R. (2024). Institutional quality and green economic growth in the West African Economic and Monetary Union. *Innovation and Green Development*, *3*(1), 100108.

Demena, B. A., & Afesorgbor, S. K. (2020). The effect of FDI on environmental emissions: Evidence from a meta-analysis. *Energy Policy*, *138*, 111192.

Emmanuel, P. M., Ugwunna, O. T., Azodo, C. C., & Adewumi, O. D. (2024). Low-carbon energy transition in oil-dependent African countries: Implication on fiscal revenue. *International Journal of Energy Sector Management*, *18*(6), 1709–1725.

Emonena, O. L., & Osifo, O. (2024). The nexus between CO2 emission, energy consumption, and economic growth in Nigeria. *EuroMid Journal of Business and Tech-Innovation*, 14–28.

Ibekilo, B., Ekesiobi, C., & Emmanuel, P. M. (2023). Heterogeneous assessment of urbanisation, energy consumption and environmental pollution in Africa: The role of regulatory quality. *Economic Change and Restructuring*, *56*(6), 4421–4444.

Ike, G. N., Usman, O., & Sarkodie, S. A. (2020). Testing the role of oil production in the environmental Kuznets curve of oil producing countries: New insights from Method of Moments Quantile Regression. *Science of the Total Environment*, *711*, 135208.

Khan, A., Hussain, J., Bano, S., & Chenggang, Y. (2020). The repercussions of foreign direct investment, renewable energy and health expenditure on environmental decay? An econometric analysis of B&RI countries. *Journal of Environmental Planning and Management*, *63*(11), 1965–1986.

Li, T., Wang, Y., & Zhao, D. (2016). Environmental Kuznets curve in China: New evidence from dynamic panel analysis. *Energy Policy*, *91*, 138–147.

Machado, J. A. F., & Silva, J. M. C. S. (2019). Quantiles via moments. *Journal of Econometrics*, *213*(1), 145–173.

Mesagan, E., Mesagan, E. P., Ogbuji, I. A., & Amadi, I. P. (2024). *Urban Energy Transition, Green Energy Access and Pollution Control: Empirical Evidence* (Vol. 66). Retrieved from https://www.researchgate.net/publication/390694673

Nwani, C., Alola, A. A., Omoke, C. P., Adeleye, B. N., & Bekun, F. V. (2022). Responding to the environmental effects of remittances and trade liberalization in net-importing economies: The role of renewable energy in sub-Saharan Africa. *Economic Change and Restructuring*, *55*(4), 2631–2661.

Odugbesan, J., Aghazadeh, S., Rjoub, H., Dantas, R., Correia, A., Rita, J., & Mata, M. (2021). Modeling the determinants of sustainable green growth in the MENAT region: Using the DCCE-MG approach. *Applied Ecology and Environmental Research*, *6*(19), 4881–4901.

Olanrele, I. A., & Fuinhas, J. A. (2024). Assessment of renewable electricity adoption in sub-Saharan Africa. *Energy & Environment*, *35*(2), 848–873.

Omri, A., Daly, S., & Nguyen, D. K. (2015). A robust analysis of the relationship between renewable energy consumption and its main drivers. *Applied Economics*, *47*(28), 2913–2923.

Orhan, A., Adebayo, T. S., Genç, S. Y., & Kirikkaleli, D. (2021). Investigating the linkage between economic growth and environmental sustainability in India: Do agriculture and trade openness matter? *Sustainability*, *13*(9), 4753.

Parajuli, R., Joshi, O., & Maraseni, T. (2019). Incorporating forests, agriculture, and energy consumption in the framework of the Environmental Kuznets Curve: A dynamic panel data approach. *Sustainability*, *11*(9), 2688.

Pesaran, M. H., Schuermann, T., & Weiner, S. M. (2004). Modeling regional interdependencies using a global error-correcting macroeconometric model. *Journal of Business & Economic Statistics*, *22*(2), 129–162.

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics*, *16*(3), 289–326.

Sadorsky, P. (2009). Renewable energy consumption and income in emerging economies. *Energy Policy*, *37*(10), 4021–4028.

Sarkodie, S. A., & Adams, S. (2018). Renewable energy, nuclear energy, and environmental pollution: Accounting for political institutional quality in South Africa. *Science of the Total Environment*, *643*, 1590–1601.

Shahbaz, M., Gozgor, G., Adom, P. K., & Hammoudeh, S. (2019). The technical decomposition of carbon emissions and the concerns about FDI and trade openness effects in the United States. *International Economics*, *159*, 56–73.

StataCorp. (2023). Stata Statistical Software: Release 18. College Station, TX: StataCorp LLC.

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World Development*, *32*(8), 1419–1439.

Tamazian, A., & Rao, B. B. (2010). Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. *Energy Economics*, *32*(1), 137–145.

Tang, J. (2015). Testing the pollution haven effect: Does the type of FDI matter? *Environmental and Resource Economics*, *60*, 549–578.

Tawiah, V., Zakari, A., & Adedoyin, F. F. (2021). Determinants of green growth in developed and developing countries. *Environmental Science and Pollution Research*, *28*(29), 39227–39242.

Torres-Reyna, O. (2007). Panel data analysis fixed and random effects using Stata (v. 4.2). *Data & Statistical Services, Priceton University*, *112*(1), 1–40.

Van Rossum, G., & Drake, F. L. (1995). *Python reference manual* (Vol. 111). Centrum voor Wiskunde en Informatica Amsterdam.

Waheed, R., Chang, D., Sarwar, S., & Chen, W. (2018). Forest, agriculture, renewable energy, and CO2 emission. *Journal of Cleaner Production*, *172*, 4231–4238.

Wang, J., Jiang, C., Li, M., Zhang, S., & Zhang, X. (2023). Renewable energy, agriculture, and carbon dioxide emissions nexus: Implications for sustainable development in sub-Saharan African countries. *Sustainable Environment Research*, *33*(1), 31.

World Bank. (2024). World Development Indicators | DataBank. Retrieved 23 July 2024, from https://databank.worldbank.org/source/world-development-indicators

Yan, Z., Zou, B., Du, K., & Li, K. (2020). Do renewable energy technology innovations promote China's green productivity growth? Fresh evidence from partially linear functional-coefficient models. *Energy Economics*, *90*, 104842.

Yang, H., Shahzadi, I., & Hussain, M. (2021). USA carbon neutrality target: Evaluating the role of environmentally adjusted multifactor productivity growth in limiting carbon emissions. *Journal of Environmental Management*, *298*, 113385.

Yasmeen, H., Tan, Q., Zameer, H., Tan, J., & Nawaz, K. (2020). Exploring the impact of technological innovation, environmental regulations and urbanization on ecological efficiency of China in the context of COP21. *Journal of Environmental Management*, *274*, 111210.

Zameer, H., & Wang, Y. (2018). Energy production system optimization: Evidence from Pakistan. *Renewable and Sustainable Energy Reviews*, *82*, 886–893.Zheng, X., Faheem, M., & Fakhriddinovch Uktamov, K. (2024). Exploring the link between economic policy uncertainty, financial development, ecological innovation and environmental degradation: Evidence from OECD countries. *PloS One*, *19*(9), e0307014.