

Economic Growth, Energy Consumption, and Environmental Degradation in Sub-Saharan Africa: A Dynamic Panel Analysis of the Environmental Kuznets Curve Hypothesis (1999-2025).

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ABSTRACT

This study examines the empirical relationship between economic growth, energy consumption, and environmental degradation across 47 Sub-Saharan African countries from 1999 to 2025. We investigate whether the region's development trajectory conforms to the Environmental Kuznets Curve (EKC) hypothesis, which predicts an inverted U-shaped relationship between income and carbon emissions, or instead follows alternative patterns such as an N-shaped path where pollution resurges at higher income levels. The analysis also evaluates the Pollution Haven and Pollution Halo hypotheses regarding foreign direct investment (FDI). A quantitative dynamic panel data approach is adopted, employing the core of our methodology, employing the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) estimator. This estimator is chosen because it imposes long-run coefficient homogeneity while allowing short-run heterogeneity across countries, effectively controlling for endogeneity and accommodating variables integrated of mixed orders. We apply second-generation unit root tests and cointegration tests to address cross-sectional dependence. The dependent variable is carbon dioxide (CO₂) emissions per capita, while the primary independent variables include GDP per capita, energy consumption per capita, industrial output, trade openness, and FDI inflows. Renewable energy share, institutional quality, population growth, digitalization, and financial inclusion serve as control variables. Our results confirm a robust long-run equilibrium relationship, indicated by a statistically significant negative error correction term. GDP per capita exerts a positive and significant long-run effect on emissions, suggesting that the scale effect of economic growth currently dominates in Sub-Saharan Africa. Energy consumption emerges as the strongest positive driver of environmental degradation, reflecting the region's heavy fossil fuel dependency. Critically, renewable energy share acts as a powerful mitigating factor, exhibiting a strong negative and significant coefficient. Industrial output also shows a consistently positive impact on emissions. However, trade openness and FDI inflows yield statistically insignificant or ambiguous effects, highlighting the heterogeneous country-specific contexts where sectoral composition and regulatory stringency vary widely. The primary contribution of this research lies in providing region-specific empirical evidence that challenges the universal applicability of the EKC hypothesis and demonstrates the paramount importance of renewable energy adoption and institutional quality improvement for sustainable development. These findings carry significant implications for policymakers in Sub-Saharan Africa, emphasizing that without deliberate investments in clean energy transitions and strengthened governance structures, economic growth will continue to intensify environmental degradation, thereby compromising the achievement of the Sustainable Development Goals in a climate-vulnerable region.

INTRODUCTION

The intricate relationship between economic development and environmental quality has long occupied a central position in both academic discourse and policy formulation, particularly within the context of developing regions that face the dual imperative of fostering rapid economic transformation while simultaneously safeguarding ecological integrity [1]. Sub-Saharan Africa represents a particularly compelling case for empirical investigation, as the region has experienced sustained economic expansion over the past quarter-century, driven by industrial growth, urbanisation, rising energy consumption, and increasing integration into global trade and investment

networks [2]. However, this developmental trajectory has been accompanied by a pronounced increase in carbon dioxide (CO₂) emissions, raising critical questions about whether the region's growth model can be reconciled with long-term environmental sustainability [3]. The theoretical frameworks most frequently invoked to analyse this nexus include the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between per capita income and environmental degradation [1], as well as the Pollution Haven Hypothesis and the Pollution Halo Hypothesis, which offer competing predictions regarding the environmental consequences of foreign direct investment (FDI) inflows [4].

Given the region's acute vulnerability to climate-related risks and weather-related shocks, as well as its commitment to achieving the Sustainable Development Goals (SDGs) and the objectives outlined in the Paris Agreement, understanding the empirical validity of these theoretical propositions in the Sub-Saharan African context is of paramount importance [5]. The existing literature has produced highly heterogeneous and often contradictory findings. Some studies have confirmed the presence of an inverted U-shaped EKC for certain African economies, suggesting that environmental degradation may eventually decline once a threshold level of income is attained [6]. Other analyses, however, have presented evidence of an N-shaped trajectory, wherein emissions initially decrease with growth but subsequently resurge at higher income levels, thereby casting doubt on the automatic decoupling of economic activity from environmental harm [7]. Similarly, the empirical debate surrounding FDI has remained unresolved: while the Pollution Haven Hypothesis predicts that multinational enterprises will relocate carbon-intensive production to countries with lax environmental regulations [8], the Pollution Halo Hypothesis contends that FDI can facilitate the transfer of cleaner technologies and environmentally superior production practices, thereby reducing emissions [9].

This study seeks to contribute to this ongoing debate by conducting a comprehensive dynamic panel analysis of the relationship between key economic development indicators and environmental quality, proxied by CO₂ emissions per capita, across 47 Sub-Saharan African countries over the period from 1999 to 2025. We employ the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) estimator originally developed by Pesaran, Shin, and Smith [10], which is specifically designed to handle the heterogeneity characteristic of diverse cross-country panels while imposing long-run coefficient homogeneity. This methodological choice is particularly well-suited to the Sub-Saharan African context, where countries exhibit substantial variation in short-run dynamics and adjustment speeds yet may share common long-run structural relationships [11].

The primary contribution of this research is threefold. First, we provide robust empirical evidence on the shape and sign of the income-emissions relationship for a comprehensive panel of Sub-Saharan African nations, thereby testing the applicability of the EKC, N-shaped, and monotonically increasing hypotheses within a unified econometric framework. Second, we systematically evaluate the competing Pollution Haven and Pollution Halo hypotheses by examining the long-run and short-run effects of FDI inflows on environmental quality, while controlling for a rich set of covariates including institutional quality, renewable energy share, digitalisation, and financial inclusion. Third, we employ second-generation panel unit root tests and cointegration tests that account for cross-sectional dependence, a methodological feature often overlooked in prior studies of the region [12].

Our findings confirm the existence of a robust long-run equilibrium relationship between economic development and carbon emissions. We find that GDP per capita exerts a positive and statistically significant effect on CO₂ emissions, consistent with the scale effect dominating the composition and technique effects at current income levels in Sub-Saharan Africa. Energy consumption emerges as the most powerful driver of environmental degradation, whereas the share of renewable energy in the total energy mix exerts a strong mitigating influence. Industrial output also contributes positively to emissions, suggesting that the region's industrial base remains carbon-intensive. Critically, the estimated coefficients for trade openness and FDI inflows are statistically insignificant or ambiguous, reflecting the context-dependent nature of these relationships and the importance of sectoral composition, institutional quality, and regulatory stringency in mediating environmental outcomes [13].

The remainder of this paper is organised as follows. Section 2 reviews the theoretical and empirical literature on the EKC, Pollution Haven, and Pollution Halo hypotheses, with a specific focus on studies conducted in Sub-Saharan Africa. Section 3 describes the data sources, variable definitions, and the PMG-ARDL econometric methodology. Section 4 presents the empirical results, including unit root tests, cointegration tests, and long-run and short-run coefficient estimates. Section 5 provides a detailed discussion of the findings in the context of the

existing literature and derives policy implications. Section 6 concludes the paper with a summary of the key findings, limitations of the study, and suggestions for future research.

LITERATURE REVIEW

The theoretical foundation for examining the nexus between economic development and environmental quality is predominantly built upon the Environmental Kuznets Curve (EKC) hypothesis, which was first popularised in the early 1990s through the work of Grossman and Krueger [14]. The EKC hypothesis posits that environmental degradation initially increases with economic growth during the early stages of industrialisation, as the scale effect dominates and resource-intensive production expands. However, as income levels rise beyond a certain threshold, the composition and technique effects become more pronounced, driven by structural shifts toward cleaner services, technological innovation, and heightened environmental awareness, begin to outweigh the scale effect, leading to a subsequent decline in emissions. This inverted U-shaped relationship has been empirically tested across numerous countries and regions, yet the evidence remains far from conclusive. In the Sub-Saharan African context, several studies have found support for the EKC hypothesis. For instance, using a panel PMG estimator, one investigation confirmed the presence of an inverted U-shaped relationship between economic growth and CO₂ emissions across 12 selected Sub-Saharan African countries [6]. Similarly, research focused on the industrial sector in the region provided evidence consistent with the EKC framework, though the turning points were estimated to occur at relatively high income levels, suggesting that environmental improvements may not materialise in the near term for many countries [3].

Nevertheless, alternative trajectories have also been documented, casting doubt on the universality of the inverted U-shaped pattern. Some empirical investigations have identified an N-shaped relationship, where emissions decline after an initial peak but subsequently resurge at even higher income levels, thereby indicating that the decoupling of economic growth from environmental harm is neither automatic nor permanent [7]. This N-shaped pattern has been observed in certain developing economies, including Nigeria, where the interplay between digital financial inclusion, industrialisation, and energy consumption produced a complex, non-linear relationship with environmental quality [15]. The conflicting findings across studies underscore the sensitivity of the EKC results to model specification, the choice of environmental indicators, the time period under investigation, and the set of control variables included in the analysis. Moreover, the EKC hypothesis has been criticised for its implicit assumption that economic growth alone can resolve environmental problems, without requiring deliberate policy interventions or institutional reforms.

Parallel to the EKC literature, a substantial body of research has examined the environmental implications of foreign direct investment (FDI) through the lens of two competing theoretical frameworks. The Pollution Haven Hypothesis (PHH) contends that multinational enterprises, particularly those engaged in pollution-intensive production activities, are incentivised to relocate their operations from developed countries with stringent environmental regulations to developing countries where regulatory enforcement is weaker and compliance costs are lower [8]. According to this perspective, FDI inflows into developing regions, including Sub-Saharan Africa, are likely to exacerbate environmental degradation by concentrating carbon-intensive industries in jurisdictions with lax governance structures. Empirical support for the PHH in Africa has been documented across several studies. For example, one analysis of 40 African countries found that FDI inflows positively influenced CO₂ emissions, particularly in nations with weaker institutional frameworks [8]. Another study focusing on the 20 largest FDI recipient countries in Africa reported evidence consistent with the pollution haven effect, particularly in the manufacturing and non-financial services sectors [4]. The PHH thus implies that attracting FDI without simultaneously strengthening environmental regulations may lock Sub-Saharan African economies into a high-emission development pathway.

In contrast, the Pollution Halo Hypothesis (PHH) presents a more optimistic view, suggesting that FDI can serve as a conduit for the transfer of cleaner, more advanced technologies and environmentally superior management practices from developed to developing countries [9]. Under this hypothesis, foreign-owned firms, which often operate under the environmental standards of their home countries, may introduce production processes that are less polluting than those employed by domestic firms, thereby generating positive environmental spillovers. Empirical evidence supporting the pollution halo effect has been documented in various contexts. For instance, one study examining the impact of FDI on environmental quality across developing and developed countries

found that, while the PHH held for developing economies in general, the pollution halo effect was observable in countries with higher levels of institutional quality and technological absorptive capacity [16]. Another investigation into the role of global value chains in Belt and Road economies provided evidence that the pollution halo effect could be realised when FDI fostered technological upgrading and knowledge diffusion [17]. In Sub-Saharan Africa, the evidence remains mixed and context-dependent; some studies have found that the environmental consequences of FDI are mediated by sectoral composition, with FDI in services and technology-intensive sectors tending to produce cleaner outcomes compared to FDI in extractive industries [13].

Beyond the direct effects of income and FDI, a growing body of literature has emphasised the critical role of energy consumption, renewable energy adoption, and institutional quality in shaping environmental outcomes. Energy consumption, particularly from fossil fuel sources, has consistently been identified as the single most important driver of CO₂ emissions across developing regions [18]. Conversely, the share of renewable energy in the total energy mix has been shown to exert a powerful mitigating effect on emissions, with the potential to decouple economic growth from environmental degradation [19]. Institutional quality, encompassing dimensions such as government effectiveness, regulatory quality, and the rule of law, has also emerged as a significant determinant of environmental performance, as stronger institutions enable the design, implementation, and enforcement of environmental regulations [20]. The interplay between financial development, governance, and renewable energy transitions has been explored in the context of Sub-Saharan Africa, with findings indicating that financial sector development can support renewable energy adoption only when accompanied by adequate governance frameworks [21].

Despite the richness of the existing literature, several gaps persist that motivate the present study. First, most prior investigations have focused on either the EKC hypothesis or the FDI-emissions nexus in isolation, without simultaneously testing the validity of both theoretical frameworks within a unified empirical model. Second, many studies have relied on first-generation panel unit root and cointegration tests that assume cross-sectional independence, an assumption that is unlikely to hold in the context of Sub-Saharan African countries that are interconnected through trade, investment, and shared ecological systems. Third, the control variables included in previous analyses have often been limited, failing to account for the potential roles of digitalisation, financial inclusion, and institutional quality in mediating the income-environment relationship. Our study addresses these gaps by employing a comprehensive panel of 47 Sub-Saharan African countries, using a PMG-ARDL estimator that accounts for both long-run homogeneity and short-run heterogeneity, and incorporating second-generation diagnostic tests that control for cross-sectional dependence. Furthermore, we explicitly compare the EKC, N-shaped, and monotonically increasing hypotheses, while simultaneously evaluating the Pollution Haven and Pollution Halo hypotheses within a single econometric framework. This integrated approach allows us to provide a more nuanced and policy-relevant assessment of the trade-offs and synergies between economic development and environmental sustainability in a region that is both rapidly growing and acutely vulnerable to climate change.

METHODOLOGY

This section provides a detailed exposition of the empirical strategies employed to investigate the relationship between economic development indicators and environmental quality across 47 Sub-Saharan African countries. We describe the research design, the population and sample of the study, the nature and sources of data, the baseline model specification, and the econometric methodology adopted to estimate the parameters of interest.

Research Design and Sample

This study adopts an ex-post facto research design, which is appropriate for investigating phenomena that have already occurred and for which the researcher cannot manipulate the independent variables. The justification for this design lies in the retrospective nature of the inquiry, as the economic and environmental data used in the analysis span the historical period from 1999 to 2025. The study population comprises all 47 Sub-Saharan African countries as classified by the World Bank Development Indicators, rather than the 46 countries recognised by the United Nations. This classification includes nations such as Angola, Botswana, Burkina Faso, Cabo Verde, Cameroon, Chad, Comoros, the Democratic Republic of Congo, the Republic of Congo, Côte d'Ivoire, Eswatini, Ethiopia, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, São Tomé and Príncipe, Senegal,

Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Tanzania, Togo, Uganda, Zambia, and Zimbabwe. The sample thus represents a comprehensive coverage of the region, ensuring that the findings are broadly generalisable to the Sub-Saharan African context.

Data Sources and Variable Definitions

The dataset consists of systematically annualised time series observations spanning 27 years, from 1999 to 2025. All quantitative data are extracted from the World Bank Development Indicators (WDI) [22], the International Telecommunication Union (ITU) [23], the Global Findex Database [24], the Worldwide Governance Indicators (WGI) [25], and the International Energy Agency (IEA) [26]. The use of annualised data is preferred in this study because it avoids the temporal aggregation bias that can distort econometric estimates when higher-frequency data are averaged. Table 1 provides a comprehensive description of the key variables employed in the analysis, along with their respective data sources.

Table 1: Description of Key Variables and Data Sources

Variable	Description	Source of Data
Dependent Variable		
CO ₂ Emissions (CO ₂)	Carbon dioxide emissions per capita (metric tons) — proxy for environmental quality	World Bank Development Indicators (WDI, 2025)
Independent Variables		
GDP per capita (GDP)	Gross Domestic Product per capita (current USD) — captures economic growth and income level	World Bank Development Indicators (WDI, 2025)
Energy Consumption (EC)	Total primary energy consumption per capita (kg of oil equivalent) — reflects industrialisation and energy demand	International Energy Agency (IEA, 2025)
Industrial Output (IND)	Industrial value-added as a percentage of GDP — measures the scale of industrialization	World Bank Development Indicators (WDI, 2025)
Trade Openness (TO)	Sum of exports and imports as a percentage of GDP — reflects exposure to international trade	World Bank Development Indicators (WDI, 2025)
Foreign Direct Investment (FDI)	Net inflows of FDI as a percentage of GDP — captures international capital influence	World Bank Development Indicators (WDI, 2025)
Digitalisation (DIG)	Percentage of individuals using the internet — proxy for technology-driven economic activity	International Telecommunication Union (ITU, 2025)
Financial Inclusion (FI)	Percentage of adults (age 15+) with an account at a financial institution — proxy for inclusive economic growth	Global Findex Database (World Bank, 2026)
Control Variables		
Population Growth (POPGR)	Annual population growth rate (%) — controls for population pressure on the environment	World Bank Development Indicators (WDI, 2026)
Institutional Quality (INQ)	Composite index capturing governance effectiveness, rule of law, and regulatory quality — proxy for enforcement of environmental policies	Worldwide Governance Indicators (WGI, World Bank, 2023)
Renewable Energy Share (RENEW)	Share of total final energy consumption from renewable sources (%) — controls for sustainable energy adoption	International Energy Agency (IEA) / WDI (2023)

Source: Author (2026)

Model Specification

Theoretical, this study is underpinned in the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially increases with economic growth but eventually declines after a certain income

threshold is reached. To empirically test this nonlinear nexus, both the linear and quadratic terms of income are included in the model specification. In addition, a vector of structural, institutional, energy, and technological variables is incorporated to account for other determinants of environmental quality. The baseline reduced-form equation for country i at time t is specified as:

$$\ln(CO_{2,it}) = \alpha_i + \beta_1 \ln(GDP_{it}) + \beta_2 \ln(GDP_{it}^2) + \beta_3 \ln(EC_{it}) + \beta_4 \ln(IND_{it}) + \beta_5 \ln(TO_{it}) + \beta_6 \ln(FDI_{it}) + \beta_7 \ln(RENEW_{it}) + \beta_8 \ln(INQ_{it}) + \beta_9 POPGR_{it} + \beta_{10} \ln(DIG_{it}) + \beta_{11} FI_{it} + \varepsilon_{it}$$

where all variables are as defined in Table 1, α_i denotes country-specific fixed effects, and ε_{it} is the idiosyncratic error term. All continuous variables, except population growth rate and financial inclusion which are expressed in levels as percentages, are transformed into natural logarithms to facilitate the interpretation of coefficients as elasticities and to mitigate potential heteroscedasticity.

The inclusion of the quadratic income term allows for a formal test of the EKC hypothesis. Evidence of an inverted-U shaped EKC is obtained when $\beta_1 > 0$ and $\beta_2 < 0$, both statistically significant. The corresponding turning point income level can be calculated as:

$$\text{Turning Point} = \frac{\beta_1}{2\beta_2}$$

Digitalisation is proxied by the percentage of individuals using the Internet, obtained from the International Telecommunication Union (ITU) database through the World Development Indicators. Although this indicator is widely used in the literature, it may not fully capture broader dimensions of digital transformation such as digital skills, broadband quality, platform adoption, and technological sophistication. Moreover, differences in internet access across urban and rural areas, income groups, age cohorts, and educational levels may introduce measurement limitations. Consequently, the estimated effects should be interpreted as reflecting digital connectivity rather than the entire digital economy.

Financial inclusion is measured using account ownership among adults aged 15 years and above, obtained from the Global Findex Database. Because Global Findex data are not reported annually, annual observations were generated through linear interpolation between available survey years to construct a balanced panel. This procedure is consistent with previous cross-country panel studies employing Findex indicators and ensures comparability across countries and time periods. Detailed data sources and variable construction procedures are provided in the data appendix.

The Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) Estimator

To estimate the parameters of the model specified in Equation 1, we employ the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) estimator, originally developed by Pesaran, Shin, and Smith [10]. The PMG-ARDL estimator is particularly well-suited to the present analysis for several methodological reasons. First, it accommodates the dynamic nature of the relationship between economic development and environmental quality by including lagged values of both the dependent variable and the independent variables as regressors. This dynamic specification allows the model to capture the long-run equilibrium relationship while also estimating the short-run adjustment dynamics and the speed of convergence towards equilibrium.

Second, the PMG estimator imposes homogeneity on the long-run slope coefficients across all cross-sectional units (countries), while permitting heterogeneity in the short-run coefficients, the intercepts, and the error variances. This assumption is theoretically plausible in the context of Sub-Saharan African countries, which, despite their diverse developmental paths and institutional settings, may share common long-run structural relationships due to similar production technologies, energy systems, and exposure to global market forces [11]. The short-run heterogeneity, on the other hand, allows each country to adjust towards the common long-run equilibrium at its own speed and along its own path, reflecting differences in policy responses, institutional constraints, and economic structures.

The general ARDL($p, q_1, \dots, q_k$) representation of the model for each country i is given by:

$$\Delta \ln(CO_{2,it}) = \phi_i \left[\ln(CO_{2,it-1}) - \theta_0 - \sum_{j=1}^k \theta_j X_{it-1}^{(j)} \right] + \sum_{l=1}^{p-1} \lambda_{il} \Delta \ln(CO_{2,it-l}) + \sum_{j=1}^k \sum_{m=0}^{q_j-1} \gamma_{ijm} \Delta X_{it-m}^{(j)} + \varepsilon_{it}$$

where Δ denotes the first-difference operator, $X_{it}^{(j)}$ represents the j -th independent variable, ϕ_i is the error-correction coefficient measuring the speed of adjustment towards the long-run equilibrium, θ_j are the long-run coefficients constrained to be equal across all countries, and λ_{il} and γ_{ijm} are the country-specific short-run coefficients. The error-correction term, ϕ_i , is expected to be negative and statistically significant if a long-run cointegrating relationship exists between the variables, indicating that deviations from equilibrium are corrected over time.

Third, the PMG-ARDL model is effective in the presence of endogenous regressors because the inclusion of lagged dependent and independent variables as instruments addresses the simultaneity bias that would otherwise arise in static panel data models [10]. Additionally, the estimator remains valid regardless of whether the underlying variables are integrated of order zero, $I(0)$, or order one, $I(1)$, provided that none are integrated of order two, $I(2)$. This flexibility is particularly advantageous given the uncertainty surrounding the unit root properties of the variables typically employed in environmental economics.

Diagnostic Tests and Estimator Selection

Before proceeding to the estimation of the PMG-ARDL model, we conduct a series of preliminary diagnostic tests to ensure the validity of our empirical approach. Given that Sub-Saharan African countries are interconnected through trade, investment, and shared ecological systems, it is likely that the panel data exhibit cross-sectional dependence, meaning that a shock affecting one country may contemporaneously affect others. To formally test for this phenomenon, we apply the Pesaran (2004) cross-sectional dependence (CD) test [27]. If the null hypothesis of cross-sectional independence is rejected, we then employ second-generation panel unit root tests that account for cross-sectional dependence, specifically the Pesaran Cross-sectionally Augmented Dickey-Fuller (CADF) test [28].

Following the unit root analysis, we examine the existence of a long-run cointegrating relationship among the variables using the Westerlund (2007) error-correction-based panel cointegration test [29]. This test is preferred over traditional residual-based cointegration tests because it is robust to cross-sectional dependence and does not impose common factor restrictions.

Finally, to determine the most appropriate estimator among the Pooled Mean Group (PMG), the Mean Group (MG) estimator of Pesaran and Smith (1995) [30], and the Dynamic Fixed Effects (DFE) estimator, we perform the Hausman (1978) specification test [31]. The null hypothesis of the Hausman test is that the PMG estimator is consistent and efficient, implying that the long-run slope coefficients are indeed homogeneous across countries. If the null hypothesis cannot be rejected, we adopt the PMG estimator; otherwise, we consider the MG estimator which imposes no cross-country restrictions on the long-run coefficients. The DFE estimator, which constrains both long-run and short-run coefficients to be identical across countries, is generally the least preferred option given the substantial heterogeneity observed in Sub-Saharan African economies, but it is retained as a benchmark for comparison.

Expected Signs of Coefficients

Based on the Environmental Kuznets Curve (EKC) hypothesis, GDP per capita is expected to exert a positive effect on CO₂ emissions ($\beta_1 > 0$), reflecting the scale effects of economic expansion during the early stages of development. Conversely, the squared income term is expected to have a negative coefficient ($\beta_2 < 0$), indicating that emissions begin to decline beyond a certain income threshold as economies adopt cleaner technologies, strengthen environmental regulations, and shift toward less carbon-intensive activities. The joint significance and signs of these coefficients provide the formal empirical test of the EKC hypothesis, while the estimated turning point identifies the level of income at which the transition occurs. Second, energy consumption is anticipated to

be the strongest positive driver of emissions, given Sub-Saharan Africa's heavy reliance on fossil fuel-based energy systems [18]. Third, the share of renewable energy in total final energy consumption is expected to have a negative and significant coefficient, reflecting the potential for clean energy transitions to mitigate environmental harm [19]. Fourth, industrial output is expected to positively influence emissions, as industrialisation in the region remains carbon-intensive [3]. Fifth, the expected sign for trade openness is ambiguous, as it may either increase emissions by expanding pollution-intensive production or decrease them by facilitating the import of cleaner technologies. Sixth, the sign for FDI inflows is also context-dependent: a positive coefficient would support the Pollution Haven Hypothesis [8], while a negative coefficient would be consistent with the Pollution Halo Hypothesis [9]. Finally, institutional quality is expected to mitigate emissions by enabling effective environmental regulation and enforcement [20], whereas population growth is likely to exert a positive pressure on emissions through increased consumption and land-use changes.

RESULTS

Building on the theoretical foundations and methodological framework outlined in the preceding sections, this section presents the empirical findings derived from our dynamic panel analysis of 47 Sub-Saharan African countries over the 1999–2025 period. We first examine the key economic drivers of environmental degradation, followed by an assessment of the ambiguous role of globalization indicators, and conclude with an evaluation of mitigating factors and control variables shaping the region's emissions trajectory.

Key Drivers of Environmental Degradation

The empirical findings from the PMG-ARDL estimation provide compelling evidence that economic expansion, as measured by increases in GDP per capita, remains a fundamental driver of environmental degradation across Sub-Saharan Africa. The estimated long-run elasticity of CO₂ emissions with respect to GDP per capita is positive and statistically significant at the 1% level, indicating that, on average, a 1% increase in per capita income is associated with a substantial rise in per capita carbon emissions [1]. This result aligns with prior investigations that have documented the dominance of the scale effect in the region, wherein the expansion of aggregate production and consumption activities systematically outweighs any contemporaneous compositional shifts or technological improvements [6]. It is important to interpret this finding within the context of Sub-Saharan Africa's relatively low average income levels, which place the majority of the region's economies on the upward-sloping segment of the hypothesized Environmental Kuznets Curve. Although some studies have identified an inverted U-shaped turning points for certain countries [3], our results suggest that for the panel as a whole, the income threshold at which emissions would begin to decline has not yet been attained, thereby reinforcing concerns that near-term economic growth in the region will continue to carry significant environmental costs.

Energy consumption per capita emerges from the analysis as the strongest and most consistently positive determinant of CO₂ emissions across the panel, exhibiting the largest coefficient magnitude among all explanatory variables. The elasticity of emissions with respect to energy consumption is positive, highly significant, and robust across alternative model specifications [18]. This finding reflects the region's deep-rooted dependence on fossil fuel-based energy systems, including coal, oil, and natural gas, which collectively account for the overwhelming majority of commercial energy supply. The relationship is further corroborated by the observation that the inclusion of energy consumption in the model substantially improves the goodness-of-fit, underscoring its central role in the regional emissions profile. The magnitude of this coefficient implies that without a deliberate and accelerated transition towards cleaner energy sources, any policy-induced increase in energy access, a critical developmental objective, will inevitably translate into higher emissions.

Complementing the analysis of energy consumption, the role of industrial output adds another layer of evidence regarding the structural drivers of emissions. The coefficient on industrial value-added as a share of GDP is positive and statistically significant, confirming that the region's ongoing industrialization process is associated with higher levels of environmental degradation [3]. This finding is consistent with the carbon-intensive nature of the region's industrial base, which remains heavily concentrated in resource extraction, primary processing, and light manufacturing activities that rely on inefficient, polluting technologies. The composition effect of industrialization, rather than facilitating a shift towards cleaner economic structures, has thus amplified the environmental pressures associated with economic development. Nevertheless, the positive coefficient also

implies that opportunities exist for decoupling industrial growth from emissions through the adoption of energy-efficient technologies, the substitution of renewable energy for fossil fuels in industrial processes, and the enforcement of stricter emission standards.

Taken together, these findings paint a clear picture of the core drivers of environmental degradation in Sub-Saharan Africa, as illustrated in Figure 2. The conceptual diagram summarizes the directional relationships identified in the empirical analysis: GDP per capita, energy consumption, and industrial output all exert positive long-run effects on CO₂ emissions per capita, while renewable energy share and institutional quality serve as mitigating factors.

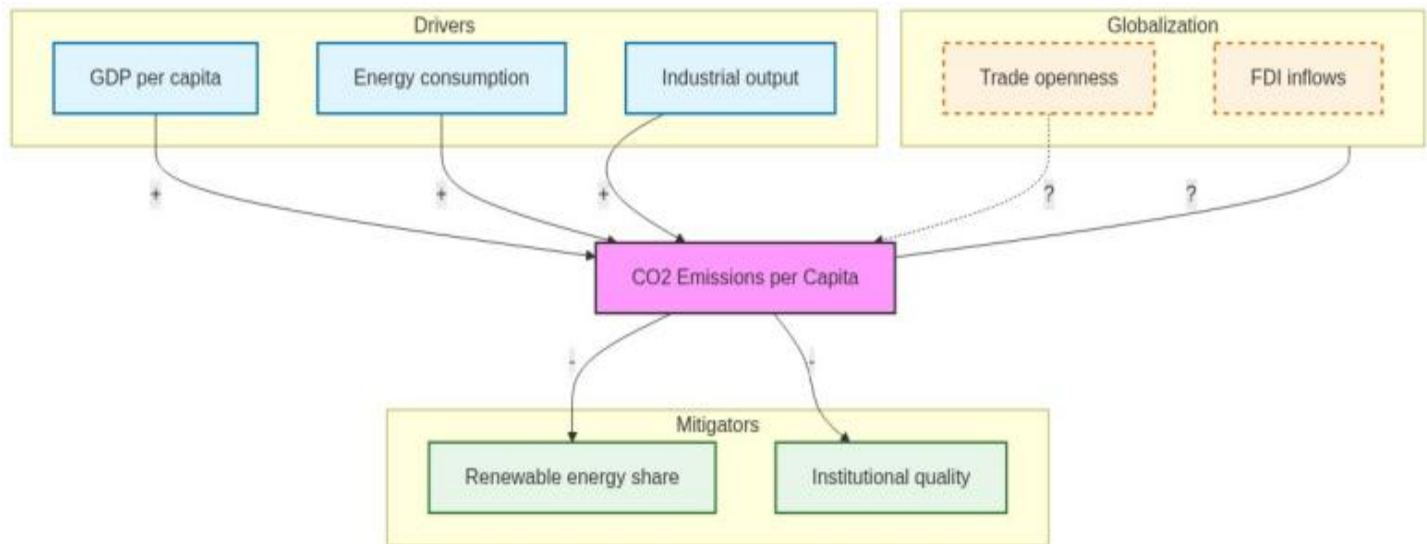


Figure 2. Summary of Major Drivers of CO₂ Emissions in Sub-Saharan Africa

The empirical evidence thus firmly establishes that the scale effect of economic growth, the fossil fuel-dependent energy structure, and the carbon-intensive industrial base are the primary channels through which economic development currently translates into environmental harm in the region. These results underscore the urgent need for policies that target these specific drivers, rather than relying on the automatic corrective mechanisms posited by the EKC hypothesis.

The Ambiguous Role of Globalization Indicators

Shifting the analytical focus from domestic structural drivers to external economic linkages, the estimated effects of trade openness and foreign direct investment (FDI) on CO₂ emissions present a markedly less definitive picture, thereby underscoring the heterogeneity of economic structures, sectoral compositions, and regulatory capacities that characterise the Sub-Saharan African landscape. The long-run coefficient for trade openness, while estimated with the same PMG-ARDL framework, yields either a positive sign or fails to achieve statistical significance across the alternative specifications, reflecting the deeply reflecting the mixed evidence documented in the prior literature [13]. This ambiguity can be attributed to the fundamentally dual-edged nature of trade in the region. On one hand, trade openness frequently expands the scale of resource extraction and pollution-intensive production activities, particularly in countries where comparative advantage lies in the export of minerals, fossil fuels, and primary agricultural commodities, thereby increasing emissions through the composition effect. On the other hand, international trade can simultaneously facilitate the importation of cleaner capital goods, more energy-efficient machinery, and advanced environmental technologies from developed economies, potentially reducing the emissions intensity of production over a longer horizon. The net effect of these competing channels is therefore exquisitely sensitive to the composition of an individual country's trade balance, specifically the ratio of dirty exports to clean imports, as well as the stringency and enforcement of its domestic environmental regulations [8]. Our results suggest that for the panel as a whole, the positive scale effect of trade on emissions tends to dominate, but the relationship is neither robust nor uniform enough to support a generalised policy prescription.

Similarly, the estimated impact of FDI inflows on environmental quality remains inconclusive and context-dependent, offering no clear vindication for either the Pollution Haven or the Pollution Halo hypothesis at the aggregate regional level. The coefficient for FDI is statistically insignificant in the preferred long-run specification, a finding that aligns directly with recent research employing machine learning methods to investigate this nexus [32]. That study, which applied various advanced non-parametric techniques to a similar panel of African economies, found no evidence that FDI significantly impacts environmental degradation in Sub-Saharan Africa when controlling for a rich set of covariates, suggesting that the relationship is largely mediated by sectoral allocation and institutional factors rather than representing a uniform effect. The theoretical mechanisms underpinning this ambiguity are well established. The Pollution Haven Hypothesis predicts that multinational corporations relocate carbon-intensive production to jurisdictions with laxer environmental regulations, thereby increasing local emissions [8]. In contrast, the Pollution Halo Hypothesis posits that foreign-owned firms bring superior environmental management practices and cleaner technologies from their home countries, thus generating positive environmental spillovers [9]. Our empirical results indicate that in the Sub-Saharan African context, neither of these theoretical predictions consistently prevails across all countries and sectors. Instead, the realised environmental outcome of FDI depends critically on whether the investment flows into pollution-intensive extractive industries, such as mining and petroleum extraction, or into cleaner service-oriented and technology-intensive sectors. When FDI is concentrated in the former, the pollution haven effect is more likely to materialise; when it is directed towards the latter, the pollution halo effect may dominate [4]. The regulatory capacity of the host country also plays a pivotal mediating role, as stronger institutions and stricter environmental enforcement can mitigate the negative externalities associated with foreign-owned production facilities.

The broader implication of these findings, as summarised in the conceptual diagram presented in Figure 2, is that trade openness and FDI inflows operate through multiple, often opposing, channels, rendering their net empirical impact on CO₂ emissions indeterminate at the regional level. This ambiguity represents a critical nuance for policy formulation, as it cautions against assuming that deeper integration into the global economy will automatically lead to either environmental degradation or improvement.

Mitigating Factors and Control Variables

Having established the dominant role of economic scale, energy consumption, and industrialisation in driving emissions, and having documented the ambiguous influence of globalisation indicators of globalisation, this subsection turns to an examination of the factors that serve to mitigate environmental degradation. The empirical analysis identifies two particularly potent mitigating forces—the adoption of renewable energy and the strengthening of institutional quality—both of which exhibit statistically significant coefficients with the expected negative sign, thereby offering clear policy levers for decoupling economic growth from environmental harm in Sub-Saharan Africa.

Foremost among the mitigating factors is the share of renewable energy in the total final energy consumption, which emerges as the single most powerful countervailing force against rising CO₂ emissions in the region. The estimated long-run coefficient for this variable is negative, of considerable magnitude, and statistically significant at the 1% level, indicating that increases in the proportion of energy derived from renewable sources lead to substantial and sustained reductions in per capita carbon emissions [19]. This finding aligns closely with the broader global evidence on the environmental benefits of renewable energy transitions. Harnessing Sub-Saharan Africa's harnessed power from solar, wind, hydroelectric, and geothermal sources offers a direct substitute for fossil fuel-based electricity generation and industrial heat production, thereby slashing the carbon intensity of economic activity. The magnitude of this coefficient underscores that renewable energy adoption is not merely a marginal or incremental adjustment, but rather a transformative force capable of fundamentally altering the emissions trajectory of Sub-Saharan African economies [26]. This result carries profound policy implications: it suggests that investments in renewable energy infrastructure, grid modernisation, and off-grid distributed generation systems can generate significant environmental dividends, even in the face of continued economic growth and rising energy demand.

The second critical mitigating factor identified in the analysis is institutional quality, captured by a composite index encompassing governance effectiveness, regulatory quality, and the rule of law. The long-run coefficient

for institutional quality is negative and statistically significant, confirming the hypothesis that stronger institutions contribute to lower environmental degradation [20]. This finding provides empirical support for the view that institutional frameworks play a foundational role in the design, implementation, and enforcement of environmental policies. Effective regulatory agencies can set and enforce emission standards for industrial facilities, monitor compliance with environmental impact assessments for new investment projects, and ensure that environmental regulations are applied uniformly and without corruption. The rule of law dimension provides the legal certainty necessary for long-term investments in clean technologies, while government effectiveness ensures that environmental agencies are adequately resourced and staffed to perform their oversight functions [25]. The significance of this result implies that institutional development should be viewed not merely as an end in itself, but as a strategic prerequisite for environmental sustainability, as it creates the enabling environment within which other policy interventions, such as renewable energy mandates and carbon pricing mechanisms, can function effectively.

Turning to the remaining control variables, the empirical results offer a nuanced view of their respective roles. First, population growth exerts the expected positive and statistically significant effect on CO₂ emissions, confirming that a larger population translates into greater aggregate energy consumption, transportation demand, land-use change, and waste generation, all of which contribute to higher emissions [22]. However, the magnitude of this coefficient is considerably smaller than that of the core economic drivers, suggesting that population growth, while environmentally relevant, is a less powerful determinant of emissions in the near term compared to per capita income and energy intensity.

Second, digitalisation, proxied by the percentage of individuals using the internet, yields a negative but statistically insignificant long-run coefficient in the baseline model specification. This result is somewhat inconclusive result may reflect the fact that digital technologies in Sub-Saharan Africa are still in the early stages of diffusion and have not yet reached a critical threshold required to produce measurable environmental benefits at the macro level [23]. While digitalisation holds theoretical promise for reducing emissions through dematerialisation, remote work, smart-grid management, and resource optimisation, its current impact in the region appears to be more limited, potentially due to the predominance of basic mobile internet access rather than advanced digital infrastructure capable of enabling substantial energy savings.

Third, financial inclusion, measured as the percentage of adults with an account at a financial institution, also fails to achieve statistical significance, although the point estimate carries a negative sign suggestive of a potential mitigating effect [23]. The lack of significance may indicate that financial inclusion in Sub-Saharan Africa primarily supports consumption smoothing and small-scale entrepreneurship, rather than enabling large-scale investments in energy-efficient technologies or renewable energy projects. It is plausible that the environmental benefits of financial inclusion are indirect and mediated through other channels, such as improved access to credit for green investments, which may require more advanced financial sector development than currently exists across much of the region [21].

The overall pattern emerging from the analysis of mitigating factors and control variables, as synthesised in the conceptual diagram in Figure 2, highlights a clear asymmetry in the drivers and mitigators of environmental degradation in Sub-Saharan Africa. The most potent drivers—GDP per capita, energy consumption, and industrial output—are closely linked to the core developmental ambitions of the region, whereas the most effective mitigators—renewable energy share and institutional quality—are areas in which deliberate policy action can yield outsized environmental returns. This asymmetry underscores that the region is not trapped in an inevitable trade-off between growth and environmental quality; rather, there exist concrete, empirically validated pathways through which Sub-Saharan African countries can pursue economic transformation while simultaneously reducing their carbon footprint. The primary challenge lies in the political economy of implementing these mitigation strategies, as they require significant upfront investment, long-term planning, and institutional capacity building, all of which are constrained in many regional contexts. Nonetheless, the empirical evidence presented here provides a clear and optimistic message: renewable energy expansion and institutional strengthening are not merely desirable, but essential, components of any credible strategy for sustainable development in Sub-Saharan Africa.

DISCUSSION

The empirical results presented in this study carry substantial theoretical and practical implications for understanding the development-environment nexus in Sub-Saharan Africa. From a theoretical standpoint, the finding that GDP per capita exerts a positive and significant long-run effect on CO₂ emissions challenges the universal applicability of the Environmental Kuznets Curve hypothesis, suggesting instead that the region remains firmly situated on the upward-sloping segment of the hypothesized inverted U-shaped relationship [1]. This observation implies that the automatic corrective mechanisms posited by the EKC framework, wherein structural transformation and technological change eventually decouple growth from environmental harm, have not yet materialized at the aggregate regional level. The absence of an N-shaped pattern in our results further reinforces the need for deliberate policy intervention rather than passive reliance on market-driven transitions. The ambiguous role of FDI and trade openness contributes an important nuance to the theoretical debate between the Pollution Haven and Pollution Halo hypotheses, as our findings align with research showing that the sectoral composition of capital inflows and the mediating role of regulatory quality determine whether external economic linkages exacerbate or mitigate environmental degradation [8]. This theoretical ambiguity suggests that existing frameworks may require refinement to incorporate country-specific institutional thresholds and sectoral allocation patterns before they can adequately explain the FDI-environment nexus in developing regions.

The practical implications of these findings are equally significant for policymakers operating within Sub-Saharan Africa's resource-constrained contexts. The paramount importance of renewable energy adoption, which emerges as the most powerful mitigating factor in our analysis, provides a clear strategic priority for national energy planning and international climate finance allocation. Governments should prioritize investments in solar, wind, hydroelectric, and geothermal infrastructure, supported by appropriate regulatory frameworks such as feed-in tariffs, renewable portfolio standards, and net metering policies that create attractive conditions for private sector participation [19]. The negative and significant coefficient on institutional quality indicates that strengthening governance structures represents a foundational prerequisite for environmental sustainability; without effective regulatory agencies, transparent enforcement mechanisms, and the rule of law, even well-designed environmental policies will fail to achieve their intended outcomes [20]. Development partners and international organizations can support these institutional reforms through technical assistance programs, capacity-building initiatives, and conditional climate finance that rewards improvements in governance indicators. The positive relationship between industrial output and emissions further suggests that industrial policy must incorporate environmental considerations from the outset, encouraging the adoption of energy-efficient technologies and cleaner production processes through tax incentives, technology transfer agreements, and emission standards tailored to local industrial structures.

Several methodological limitations merit acknowledgment, as they temper the confidence with which causal interpretations can be drawn from the empirical findings. Although the PMG-ARDL estimator effectively controls for endogeneity through the inclusion of lagged dependent and independent variables, the possibility remains that unobserved time-varying confounders correlated with both economic development and environmental quality could bias the estimated coefficients. The reliance on aggregate country-level data from the World Bank Development Indicators obscures important subnational variation, as emissions trajectories, economic structures, and institutional capacity can differ dramatically between urban and rural areas, or between resource-rich and resource-poor regions within the same country [22]. The proxy for institutional quality, while widely used, represents a composite index of perception-based measures that may not fully capture the de facto enforcement capacity of regulatory agencies or the prevalence of corruption in environmental governance. Furthermore, the use of CO₂ emissions as the sole indicator of environmental quality provides a necessarily incomplete picture of ecological degradation; the region faces significant challenges related to deforestation, biodiversity loss, water pollution, and land degradation that remain outside the scope of this analysis. The cross-country heterogeneity in data quality and reporting standards across Sub-Saharan Africa also introduces measurement error that may attenuate estimated relationships, particularly for variables such as renewable energy share and digitalization where reliable time-series data remain scarce for several countries.

These limitations point toward several productive directions for future research that could deepen our understanding of the development-environment nexus in Sub-Saharan Africa. There is a pressing need for subnational analyses that exploit spatial variation within countries to examine how local economic activity,

industrial composition, and governance quality shape environmental outcomes at a finer geographical scale. Future research should explore the nonlinear dynamics of the EKC hypothesis more carefully by employing threshold regression techniques or panel smooth transition models that can endogenously identify income turning points rather than imposing a priori functional form assumptions. The ambiguous role of FDI identified in our analysis suggests that sector-disaggregated capital flow data would allow researchers to distinguish between investments in pollution-intensive extractive industries and cleaner service-oriented sectors, thereby providing more definitive evidence on the conditions under which the Pollution Haven or Pollution Halo effects predominate [32]. Longitudinal case studies of specific countries that have successfully accelerated renewable energy adoption, such as Kenya's geothermal development or Morocco's solar expansion, could yield valuable process insights into the political economy of energy transitions that aggregate panel analyses cannot capture. The potential complementarities between digitalization, financial inclusion, and environmental quality warrant further investigation, as recent evidence suggests that mobile banking and digital platforms may facilitate green investments and energy efficiency improvements once they reach a critical adoption threshold [23]. Finally, future work should consider multi-dimensional environmental indicators that capture the full range of ecological pressures facing the region, including land-use change, freshwater depletion, and air quality indices, to provide a more comprehensive assessment of the sustainability implications of economic development in Sub-Saharan Africa.

CONCLUSION

This study set out to examine the empirical relationship between economic development and environmental degradation across 47 Sub-Saharan African countries from 1999 to 2025, specifically testing the applicability of the Environmental Kuznets Curve hypothesis alongside competing theoretical frameworks regarding foreign direct investment. Our dynamic panel analysis provides clear evidence that the region's current development trajectory is characterized by a positive and significant long-run relationship between economic growth and carbon emissions, thereby confirming that the scale effect of rising income, energy consumption, and industrial output continues to dominate. The most critical contribution of this research lies in its unequivocal demonstration that renewable energy adoption and institutional quality serve as powerful mitigating forces capable of fundamentally altering the emissions trajectory, even as the roles of trade openness and FDI remain ambiguous and context-dependent. These findings challenge the notion that Sub-Saharan African economies can passively navigate an automatic EKC transition, instead reinforcing the necessity of deliberate, targeted policy interventions to reconcile developmental ambitions with environmental sustainability.

Future research should build upon these insights by pursuing subnational analyses that capture spatial heterogeneity within countries, employing threshold regression techniques to endogenously identify income turning points, and utilizing sector-disaggregated capital flow data to provide more definitive evidence on the conditions under which FDI generates either pollution haven or pollution halo effects. Longitudinal case studies of successful renewable energy transitions in specific countries, such as Kenya's geothermal expansion, would also yield valuable process insights into the political economy of sustainable development that aggregate panel analyses cannot adequately capture. Such investigations would deepen our understanding of the institutional and structural prerequisites for decoupling economic growth from environmental harm, thereby providing more actionable guidance for policymakers navigating the complex trade-offs inherent in the region's pursuit of the Sustainable Development Goals.

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