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RESEARCH ARTICLE

Economic Growth, Energy Consumption, and Environmental Quality in Sub-Saharan Africa: Testing the Environmental Kuznets Curve (EKC) Hypothesis

Ebrima K. Ceesay[1*], Matarr Njie[1], Emmanuel Igbinoba[2], Etse Yawo Dzakpa[3], Mohamed Ben Omar Ndiaye[4], Amie M. Jobe[5,1], Amadou Cham[6], Ebrima B. Jallow[7], Cherno Jallow[1], Lamin B. Jammeh[1]

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Abstract

This paper empirically tests the Environmental Kuznets Curve (EKC) hypothesis for sub-Saharan Africa, using CO_2 emission as a proxy for environmental quality. The analysis employs panel pooled data for 39 countries from 1990 to 2019. We find evidence of an inverted U-shaped relationship between income and emissions, as GDP per capita has a positive effect and its square has a negative effect on CO_2 emissions, thereby supporting the EKC hypothesis.

Our results reveal a dual role for renewable energy. When CO_2 emissions are the dependent variable, renewable energy consumption significantly reduces emissions, while non-renewable energy increases them. Additionally, population size and literacy rate are found to positively affect CO_2 emissions. In contrast, when economic growth is the dependent variable, renewable energy has a positive and significant influence.

These findings indicate that expanding renewable energy production in sub-Saharan Africa offers a dual advantage, enhancing environmental quality while also contributing to stronger economic performance. By demonstrating that renewable energy reduces CO_2 emissions and supports growth, the results provide important guidance for policymakers seeking to advance sustainable development pathways that are compatible with long-term environmental conservation across the region.

Keywords EKC · CO_2 Emission · GDP per Capita Growth · Panel Pooled Estimation · Energy Consumption · Renewable Energy · Sub-Saharan Africa

1. Introduction

Countries in sub-Saharan Africa face significant environmental challenges, including higher carbon dioxide (CO_2) emissions, as they strive for economic development and improved living standards for their people. Balancing economic growth with environmental conservation is crucial to ensure sustainable development in the region.

[*] Corresponding Author: ceesayebrimak@gmail.com
[1] Department of Economics and Finance, University of the Gambia, Gambia
[2] Independent Researcher
[3] African Institute for Mathematical Sciences Research and Innovation Centre, Rwanda
[4] University Cheikh Anta Diop (UCAD), Dakar, Senegal
[5] University of Verona, Italy
[6] Kwame Nkrumah University of Science and Technology, Ghana
[7] Ministry of Finance and Economic Affairs, Gambia

Environmental degradation, measured through carbon dioxide (CO_2) emission, is therefore of critical concern for sub-Saharan African countries (Ceesay et al., 2021). These countries face the challenge of balancing economic growth and development with the need to mitigate environmental degradation.

Previous research on the relationship between economic growth, energy consumption and CO_2 emission has provided valuable insights (Kaika and Zervas, 2014). The Environmental Kuznets Curve (EKC) theory posits an inverted U-shaped relationship between GDP per capita and environmental degradation, indicating that as countries develop, environmental quality initially deteriorates but eventually improves (Ceesay et al., 2021). However, empirical studies have yielded mixed results, highlighting the need for context-specific investigations. Moreover, the energy consumption variable plays a crucial role in determining that fossil fuel-based energy sources are a significant contributor to greenhouse gas emissions (Bhattacharya, 2019). Energy consumption is a critical factor influencing CO_2 emissions in sub-Saharan African countries (Shabestari, 2018). The heavy reliance on fossil fuels for energy production, coupled with inadequate energy efficiency measures and limited access to clean and renewable energy sources, contributes significantly to CO_2 emissions (Salahuddin and Gow, 2014).

Studies have emphasised the need to transition to cleaner and more sustainable energy systems, such as promoting renewable energy technologies, improving energy efficiency and enhancing access to modern and clean energy services (Li et al., 2023). Furthermore, the literature highlights the importance of policy interventions in addressing environmental challenges in sub-Saharan Africa. Sustainable development policies that integrate environmental concerns into economic planning, such as promoting green technologies, supporting renewable energy investments and implementing energy efficiency measures, are essential for achieving both economic growth and environmental sustainability (Saleh and Hassan, 2024).

Despite the existing literature, further research is needed to understand the specific dynamics linking economic growth, GDP per capita, energy consumption and CO_2 emission in sub-Saharan African countries. It is essential to account for the region's unique socio-economic and environmental characteristics and to consider factors like population growth, education, urbanisation, R&D, technological advancement and policy frameworks when assessing their impact on environmental quality. Although numerous studies exist, few have thoroughly examined the disaggregated effects of renewable and non-renewable energy within an EKC framework specifically for sub-Saharan African countries, while simultaneously addressing methodological issues such as endogeneity and heterogeneity. This study seeks to fill these gaps by applying a robust panel econometric approach and incorporating region-specific control variables.

1.1. Research Questions

1. Does the EKC hypothesis hold in sub-Saharan African countries?
2. How do GDP and GDP per capita influence environmental quality?
3. What is the role of renewable and non-renewable energy consumption in shaping environmental outcomes?

1.2. Hypotheses

1. Hypothesis 1: H0: There is no Environmental Kuznets Curve (EKC) relationship between economic growth and environmental quality in sub-Saharan African countries.
2. Hypothesis 2: H0: GDP and GDP per capita have no statistically significant effect on environmental quality in sub-Saharan African countries.
3. Hypothesis 3: H0: Renewable and non-renewable energy consumption have no statistically significant impact on environmental quality in sub-Saharan African countries.

2. Methodology

The main aim of this paper is to test the Environmental Kuznets Curve (EKC) hypothesis for a sample of sub-Saharan African countries by examining how economic growth, GDP per capita, and energy consumption influence CO_2 emissions, which serve as indicators of environmental quality. In line with this objective, the analysis also investigates whether the EKC relationship holds across 39 countries in the region by assessing how changes in economic activity shape environmental outcomes.. It further investigates the extent to which renewable and non-renewable energy consumption shape environmental outcomes, assessing which energy sources contribute to environmental improvement or degradation. Through this analysis, the study provides a comprehensive understanding of the growth–environment–energy nexus in sub-Saharan Africa. Annual data were obtained from the Global Economy.com, covering the period 1990 to 2019. We examine the multiple ways in which economic growth is linked with renewable energy consumption, non-renewable energy consumption and other control variables for 39 sub-Saharan African countries.

The study employs a panel data estimation approach. Given the balanced nature of the dataset and the focus on common cross-country relationships, a pooled OLS model is initially used for baseline estimation. Robustness checks are conducted to address potential issues of multicollinearity and heteroskedasticity by Singh et al. (2019), Apergis et al. (2011), Zhang and Cheng (2009), Jalil and Mahmud (2009) and Chang (2010).

The empirical framework of this paper includes a set of energy, economic growth, GDP per capita, and control variables that align with the study's objectives. The core economic indicators consist of economic growth, measured as the rate of change of real GDP, and GDP per capita in current U.S. dollars. The model also incorporates the labour force (in millions of people) as a key demographic control variable. In addition, the analysis includes energy use per capita to capture the role of energy consumption in shaping environmental outcomes and renewable and non-renewable indicators. Together, these variables provide a comprehensive basis for examining the relationships among economic growth, income levels, energy consumption and environmental quality in Sub-Saharan African countries.

2.1. Empirical Framework

All of the above variables are incorporated into the Cobb-Douglas production function following the works of Nicholas and Payne (2011) and Lee and Lee (2012).

Their framework looks like this:

$$\boldsymbol{EQ_{it} = f(RE_{it}, NRE_{it}, Gdp\ per\ capita_{it}, Gdp\ per\ capita\ squared_{it}, Z_{it})} \tag{1}$$

Where: EQ_{it}: environmental quality, at time t and observation i

RE_{it}: Is the total renewable energy consumption at time t and individual *i=1,..., N; t=1,..., T.*

NRE_{it}:Total non- renewable energy consumption at time t and individual as above

$Gdp\ per\ capita_{it}$:Total GDP per capita

$Gdp\ per\ capita\ squared_{it}$: GDP per capita squared

Z_{it}: is other control variables.

Aggregate environmental quality is a function of the real capital stock (proxy variable Gross capital formation or investment), labour (Labour force proxy), energy use is of two types; renewable energy consumption (solar energy, wind power, geothermal energy, biomass from plant, hydropower electricity, and heat energy) and non-renewable energy consumption (crude oil, natural gas, and coal are also called fossil fuel, nuclear energy, petroleum, CO_2 emission) and others controls variables such as R&D, literacy rate and secondary enrolment (Proxies variables for human capita), trade openness and population size.

Hence, in its generalised form, the Cobb-Douglas production function may be written as:

$$\boldsymbol{f(x) = A\prod_{i=1}^{L} {x_i}^{\theta_i}} \tag{2}$$

Where: A is an efficiency parameter

L is the total number of goods either consumed or produced, or a combination of both

X is from$x_1, \dots, x_i$ are non-negative quantities of goods consumed, produced or a combination of both

θ: is an elasticity parameter for good and lies between 0 and 1.

In our model, we allow economic growth to be determined by renewable energy, non-renewable energy and other sets of control variables such as gross capital formation, labour force, population, literacy rate, secondary enrolment proxies for human capital, trade openness and R&D.

2.2. Environmental Kuznets Curve Hypothesis (EKC)

The study also wants to have some understanding of the EKC in the case of the energy sector in selected countries in sub-Saharan Africa, and therefore adopted equation 6 below by adding GDP per capita and GDP per capita squared to test the Environmental Kuznets Curve Hypothesis. This is important to understand whether environmental quality (proxy variable CO_2 emissions) also has important effects on the environment. To achieve this objective, the study employs the same approach proposed by Zhang and Cheng (2009), Jalil and Mahmud (2009), Chang (2010), Loom et al. (2004) and Afzal et al. (2010). Similarly, a panel framework as in Apergis and Payne (2009) is adopted following Ang (2007) and Apergis and Payne (2009), where the long-run relationship between CO_2 emission/environmental quality, total energy consumption by overall or types in renewable energy or non-renewable energy consumption and GDPPC (GDP per capita) is adopted.

To assess the validity of the Environmental Kuznets Curve Hypothesis, the study embraced the following model:

$$\boldsymbol{Ln\, EQ_{it}/CO_2 = \beta_0 + \beta_1 log\ (GDPPC_{it}) + \beta_2 log\ (GDPPC_{it})^2 + \beta_3 log\ (Z_{it}) + \beta_4\, log(RE_{it}) + \beta_5 log\ (NRE_{it}) + \varepsilon_{it}} \quad (3)$$

To account for potential endogeneity and unobserved heterogeneity, we estimate fixed-effects and random-effects models as robustness checks. We also conduct Variance Inflation Factor (VIF) tests to assess multicollinearity, and the mean VIF values remain below 5, indicating that multicollinearity is not a concern in the model.

The variables of this study are logarithmic to allow the coefficients to be interpreted as the rate of change of variables in elasticity form. $\ln EQ_{it}\ (CO_2)$ is the natural logarithm of environmental quality at time t and individual i, $\log\ (GDPPC_{it})$, is the natural logarithm of the per capita income of the selected sub-Saharan African countries, $\log\ (GDPPC_{it}{}^2)$ is per capita income square $\log\ (Z_{it})$ is the set of control variables as explained above, $\log\ (RE_{it})$ is the renewable energy (overall-total or types), $\log\ (NRE_{it})$ is non-renewable energy (overall-total or types).

To understand the existence of the Environmental Kuznets Curve in our model, we first take the derivatives of environmental quality (CO_2 as a proxy) with respect to per capita income, and we equate this to zero. Therefore, to calculate the turning point of the EKC, we use the formula: –(coefficient of the linear term) / (2 × coefficient of the squared term). It means that the coefficient of the per capita income is divided by two times the coefficient of per capita income squared. After these calculations, we check whether the resulting value falls within the range of GDP per capita or not. Thus, EKC exists at a point at which $\beta_1 > 0$, coefficient for GDP per capita and $\beta_2 < 0$, coefficient for GDP per capita squared.

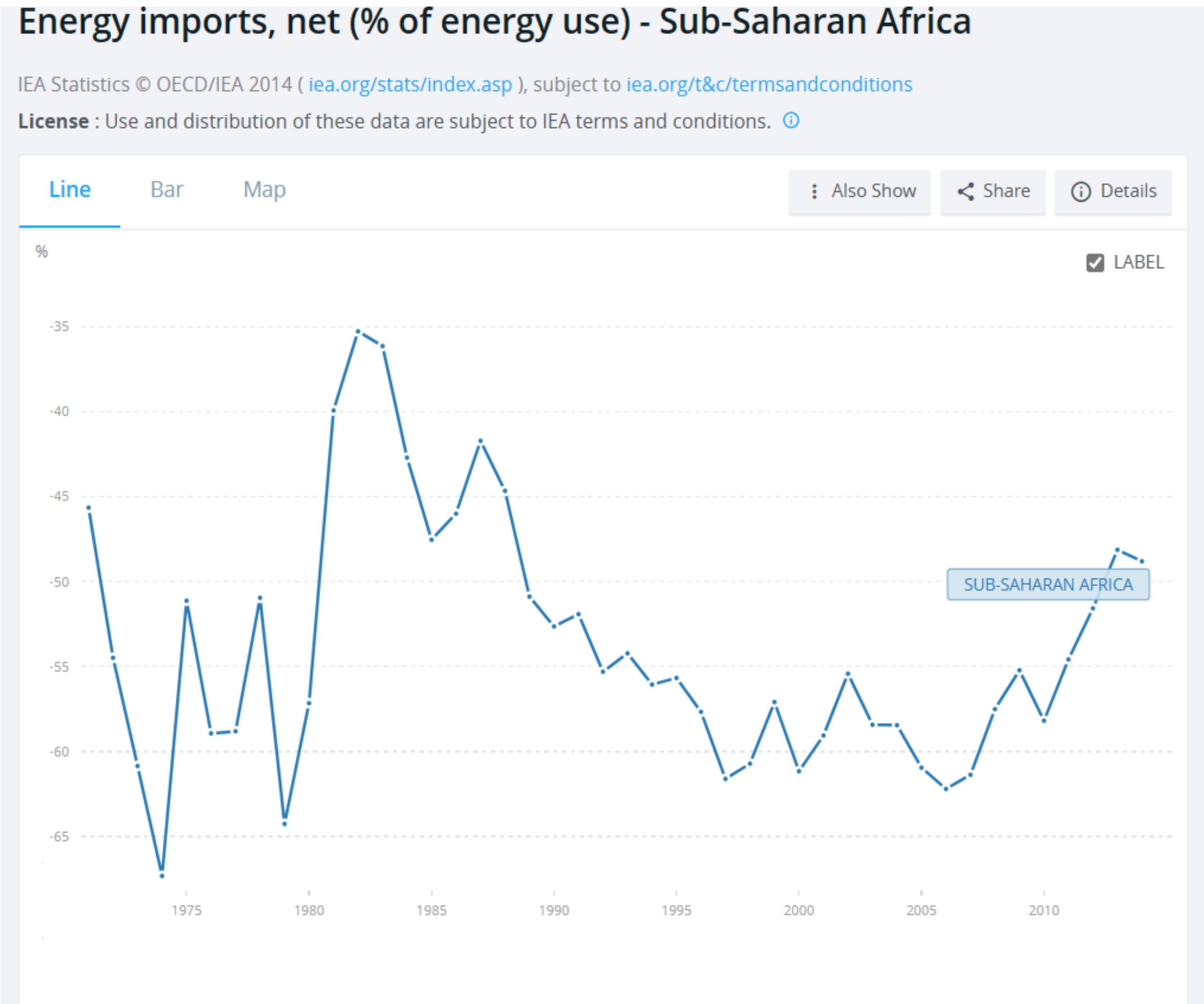

Figure 1. Energy Imports Sub-Saharan Africa,

3. Econometrics Results and Interpretation

Data sources and the definition of variables used

Variable name	Source	Comment
Economic growth	Globaleconomy	Growth of the economy over time
GDP per capita	Globaleconomy	GDP per capita over the population
Renewable energy	Globaleconomy	Energy generated from renewable sources such as solar, wind, hydro, geothermal, and biomass
Non-renewable energy	Globaleconomy	Energy generated from fossil fuels such as coal, gas, nuclear, etc...
Research and development spending	Globaleconomy	Amount spent on innovation
Literacy rate	Globaleconomy	The rate of the country stands for learning
Human capita	Globaleconomy	Measuring education in our case
Population size	Globaleconomy	The size of the country's population
CO_2 Emission	Globaleconomy	The amount of CO_2 generated in the atmosphere

3.1. Descriptive Statistics

Table 1. Descriptive statistics (Source: Computed by authors using STATA 16)

Variables	Mean	Std	Obs	Min	Max
lnEG	1.309	0.628	1131	-0.988	2.122
lnGDPPCC	7.119	0.475	1131	6.540	7.785
lnRE	0.443	0.488	1131	-1.458	1.055
lnNRE	8.517	0.145	1131	8.287	9.009
lnRD	-1.242	0.401	897	-2.465	-0.478
lnLR	3.908	0.270	1131	3.296	4.249
lnSSE	3.504	0.255	1131	3.063	3.856
PS	17.467	26.304	1131	0.420	195.87
lnCO_2 EMISSION	9.647	0.225	1131	9.292	10.052

As the summary statistics in Table 1 show, the dataset contains information on various variables for different countries over multiple time periods in years. The variables include research and development index (LnRD), population size (PS), literacy rate (LR), secondary school enrolment rate (LnSSE), economic growth rate (LnEG), and lnCO_2 EMISSION.GDP per capita Current (GDPPCC, renewable energy (LnRE) and non-renewable energy (LnNRE) with logarithmic transformations of these variables. The dataset includes summary statistics such as mean, standard deviation, minimum and maximum for each variable. The variables related to energy sources and emissions, such as carbon dioxide emissions, exhibit substantial variation across countries and over time. Moreover, based on the descriptive statistics, population size records the highest mean, standard deviation and maximum values among all variables in the dataset. This indicates that population levels differ widely across sub-Saharan African countries, and this contributes significantly to the overall variability observed in the sample.

3.2. Correlation Matrix

Table 2. Correlation matrix (Source: Computed by authors using STATA 16)

Variables	lnEG	lnGDPPCC	lnRE	lnNRE	lnRD	lnLR	lnSSE	PS	lnCO_2 emission
lnEG	1.000								
lnGDPPCC	0.02	1.000							
lnRE	-0.01	0.139	1.000						
lnNRE	-0.15	0.689	-0.396	1.000					
lnRD	-0.12	0.480	0.417	0.251	1.000				
lnLR	-0.33	0.377	0.032	0.332	0.336	1.00			
lnSSE	-0.38	0.846	0.287	0.696	0.480	0.416	1.000		
PS	-0.03	0.101	0.019	0.093	0.059	0.053	0.111	1.000	
lnCO_2 emission	-0.23	0.877	0.158	0.814	0.500	0.365	0.912	0.115	1.000

Table 2 shows the correlation matrix between the variables used in this study. As can be seen, secondary education is negatively correlated with growth (coefficient = -0.378), while literacy rate is negatively correlated with growth (coefficient = -0.326). Research and development spending increases growth by 12.3% in sub-Saharan African countries. GDP per capita increases growth by 1.5%. CO_2 emission is the most important objective of climate change finance, through which the SDG goals of climate mitigation can be achieved. The results indicate that higher CO_2 emissions are associated with weaker economic performance in sub-Saharan African countries. Specifically, the estimates show that a one-unit increase in CO_2 emissions is correlated with a 22.6% decline in economic performance, holding other factors constant. Interpreted proportionally, a 100% increase in CO_2 emissions is associated with a 22.6% reduction in economic growth.

Table 3. Levin-Lin-Chu Panel unit root test (Source: Computed by authors using STATA 16)

Variables	Level (p-value)	First difference (p-value)	statistics	Remark
RD	0.0000		-9.0023	Stationary
D.GDPPCC		0.0000	-10.6171	Stationary

We used the Levin-Lin-Chu unit-root test because of the fact that the data is a balanced panel. The results indicate the level p-value and the first difference p-value; the R&D and D.GDPPCC are stationary. Then we went on to estimate the panel model.

Table 4. Regression result of GDPPCC and GDPPCCSQ on CO_2 EMISSION (Source: Computed by authors using STATA 16)

Variables	Coef. P-value	t-ratio Std. E
Constant	1819.82***	4.96 (366.56)
GDPPCC	17.23***	29.26 (0.59)
GDPPCCSQ	-0.004***	-21.30 (0.00)
Number of observations	1131	
R-squared	0.8104	

Note: ** and *** denote significance at 5% and 1% level of significance, respectively.

To test the Environmental Kuznets Curve Hypothesis, the model includes the dependent variable CO_2 EMISSION as a proxy for environmental quality and two independent variables: GDPPCC, GDP per capita and GDPPCCSQ represents the squared term of GDPPCC in order to capture a potential nonlinear relationship. The coefficient estimates, standard errors, t-values, and p-values for each independent variable are shown in Table 4. The coefficient estimate for GDPPCC is 17.23324, with a standard error of approximately 0.59. The t-value is 29.26, and the p-value is 0.000, which indicates that GDPPCC has a statistically significant and positive effect on CO_2 emissions, which is the proxy for environmental quality. The coefficient estimate for GDPPCCSQ is -0.004, with a standard error of 0.00. The t-value is -21.30, and the p-value is 0.000. Interpretation is that, when we run the impact of GGDP per capita and GDP per capita squared on CO_2 emission as a proxy for environmental quality, we found that in the sub-Saharan African countries, a one-unit increase in GDP per capita is associated with a 2.88% rise in CO_2 emission, indicating higher environmental degradation at lower income levels. Likewise, we found that GDP per capita squared decreases CO_2 by 0.0006% approximately.

These findings support the inverted-shaped EKC hypothesis, suggesting that after reaching an income turning point, further economic growth may lead to reduced CO_2 emissions through structural and technological changes. The R-squared value of the model is 0.8104, which suggests that approximately 81.04% of the variation in the CO_2 emissions is explained by the GDP per capita, current and GDP per capita squared current. Moreover, the adjusted R-squared value is 0.8101, which takes into account the number of independent variables and the sample size. In addition, the F-test with 2 degrees of freedom in the numerator and 1128 degrees of freedom in the denominator has a test statistic of 2411.18 and a p-value of 0.000, indicating that the overall model is statistically significant. Subsequently, the root mean square error (RMSE) is 1548.7, which represents the standard deviation of the residuals. The constant term (intercept) is also included in the model. The estimated value of the intercept is 1819.817, with a standard error of 366.5559.

In conclusion, the output in Table 4 provides information about the impact of GDP per capita and GDP per capita squared and their overall effects on CO_2 emissions. This is done to test the Environmental Kuznets Curve Hypothesis for sub-Saharan African countries.

Table 5. Controlling for other variables, the dependent variable CO_2 EMISSION (Source: Computed by the authors using STATA 16)

Variables	Coef. P-value	t-ratio Std. E
Constant	5496.11***	8.58 (640.59)
GDPPCC	2.88***	9.89 (0.29)
GDPPCCSQ	-0.001***	-7.05 (0.00)
RE	-13178.36***	-7.57 (1740.08)
NRE	1.60***	14.17 (0.11)
RD	1326.17***	12.43 (106.67)
LR	0.28	0.25 (1.13)
SSE	4.22	0.69 (6.15)
PS	0.03	0.08 (0.35)
EPRE	5.92***	31.70 (0.19)
EUPC	-2.26***	-5.24 (0.43)
EI	8.92***	8.52 (1.05)
RPG	13366***	8.22 (1625.48)
Number of observations	1131	
R-squared	0.9925	

Note: ** and *** denote significance at 5% and 1% level of significance, respectively.

Subsequently, renewable energy consumption significantly reduces CO_2 emissions, with the coefficient indicating a substantial decrease in emissions per unit increase in renewable energy, while non-renewable energy use increases CO_2 emissions by 1.6. Sub-Saharan Africa has a high population, and population size has a small but statistically significant positive effect on CO_2 emissions.CO_2 Furthermore, the results reveal that research and development expenditure in sub-Saharan African countries has a positive and significant impact on CO_2 emissions.

However, electricity production from renewable energy (EPRE) has a significant positive impact on environmental quality in sub-Saharan African countries. Energy use per capita(EUPC) has a significantly negative effect on CO_2 emission, and Energy imports (EI) as a percentage of total energy use have a positive and significant influence on CO_2 emission in sub-Saharan African countries. Likewise, renewable power generation (RPG) has a positive and significant impact on CO_2 emissions. The R-squared indicated that the model is enough for the analysis. The joint significance of the model is highly significant at 99.9% alpha. The R-squared value of the model is 0.9925, indicating that approximately 99.25% of the variation in the dependent variable is explained by the independent variables. The adjusted R-squared value is 0.9924, which takes into account the number of independent variables and the sample size. The F-test with 12 degrees of freedom in the numerator and 1118 degrees of freedom in the denominator has a test statistic of 12257.36 and a p-value of 0.000, indicating that the overall model is statistically significant. The constant term (intercept) is also included in the model. The estimated value of the intercept is 5496.211, with a standard error of 640.5917.

Table 6. Dependent variable lnEG (Source: own evaluations by authors using data from globaleconomy.com)

Variables	Coef. P-value	t-ratio Std. E
Constant	0.80	0.22 (0.80)
LF	0.58***	3.86 (0.15)
GFCF	-4.52e-13	-0.26 (1.76e-12)
RE	9.70***	4.07 (2.38)
EI	-0.005***	-3.05 (0.002)
RPG	-8.91***	-4.09 (2.18)
EPRE	-0.002***	-6.07 (0.0003)
EUPC	-0.003***	-6.43 (0.0005)
SSE	-0.046***	-4.80 (0.10)
LR	-0.006***	-3.24 (0.002)
RD	0.66***	3.76 (0.18)
PS	0.0002	0.27 (0.001)
Number of observations	909	
Adjusted R-squared	0.4905	

Note: ** and *** denote significance at 5% and 1% level of significance, respectively.

In hypothesis one, the results revealed that the labour force has a significant positive influence on the growth rate of the economy. A 1 unit rise in the labour force causes the growth rate of real GDP to rise by approximately 0.58%. Gross fixed capital formation as a proxy for investment decreases growth in sub – Saharan African countries. In addition, energy import decreases economic growth by 0.5% for a 1 unit increase. Subsequently, renewable energy increases growth by 9.7%, and research and development spending increases growth by 0.66%. Population increases still do not translate into higher economic growth because both the literacy rate and secondary education exert a negative impact on growth. In addition, renewable power generation, energy use, and energy production from renewable sources all have a significantly negative effect on the economy's growth rate. The R-squared value indicated that the model is good. The F-statistic indicated that the models were jointly significant.

Table 7. Dependent variable lnGDPPCC (Source: own evaluations using data from globaleconomy.com)

Variables	Coef. P-value	t-ratio Std. E
Constant	0.69***	17.48 (0.15)
LF	0.85***	29.43 (0.03)
GFCF	-1.81e-13	-0.53 (3.39e-13)
RE	-2.81***	-6.14 (0.46)
EI	-0.001**	1.94 (0.0003)
RPG	2.54***	6.06 (0.42)
EPRE	-0.002***	-26.39 (0.0000)
EUPC	-0.001***	12.75 (0.0001)
SSE	-0.03***	-16.03 (0.002)
LR	-0.003***	-10.12 (0.0003)
RD	0.034***	-23.70 (0.034)
PS	0.0002	0.42 (0.0001)
Number of observations	909	
Adjusted R-squared	0.9671	

Note: ** and *** denote significance at 5% and 1% level of significance, respectively.

When we took GDP per capita as our endogenous variable, the results found that the labour force is still significant and positive, and energy import becomes significant and renewable energy becomes negative. Meaning renewable energy does not reach all households in sub-Saharan African countries. Henceforth, research and development spending has a negative impact on GDP per capita. Moreover, energy production from renewable sources has a negative impact, while both literacy rate and secondary education has negative impact on the growth rate of GDP per capita. However, energy use has a significant positive influence on the growth rate of GDP per capita. The R-squared value of 96.75 indicates that the model is good. The f statistic for joint significance is highly significant at 1% level of alpha.

We further tested the EKC hypothesis and found that GDPPCC has a positive impact on CO_2 emission, a proxy for environmental quality and that this was statistically significant. In addition, we also found that in the sub-Saharan African countries, when GDP per capita increases by 1 unit, the environmental quality increases by 2.88%. This is in line with the findings in Ceesay et al. (2021).

Likewise, we found that GDP per capita squared decreases CO_2, which is a proxy for environmental quality, by 0.0006% approximately. This is in the same findings as Patiño et al. (2020).

4. Discussion of the results

The results of our study also show that research and development (R&D) expenditure in sub-Saharan African countries has a positive and statistically significant effect on CO_2 emissions. This counterintuitive finding may partly reflect heteroskedasticity or endogeneity issues within the dataset, given the structural differences across countries and the limited availability of high-quality environmental data. It may also indicate that R&D spending in the region is relatively small and not primarily directed toward low-carbon technologies, making it difficult for countries to effectively manage emissions in line with the objectives of the Paris Agreement. As a result, increases in R&D may be associated with general economic expansion rather than targeted investments in green innovation, leading to higher rather than lower emissions.

This aligns with the recent findings of Elom et al. (2024), who used panel data from the World Development Indicators for thirty-two African countries over 19 years. Employing five rigorous panel regression models, Elom et al. 2024 identified a bidirectional causal relationship between carbon emission and education expenditure. Moreover, our results show that investment in education, renewable energy, and employment plays a crucial role in mitigating carbon emissions in Africa. Regarding population size, our results show that it has a significant and positive effect on CO_2 emissions, increasing emissions by approximately 0.028% for every one-unit increase in population size. This relationship is expected in the context of sub-Saharan Africa, where rapid population growth places additional pressure on already-strained environmental systems. As population size increases, more people occupy and utilise local ecosystems, often contributing to higher emissions through increased household energy use, agricultural expansion, and waste generation. In many rural and peri-urban areas, inadequate waste management systems lead to open dumping and burning, which further elevate CO_2 and other greenhouse gas emissions. This finding may also reflect heteroskedasticity or endogeneity issues within the dataset, given the structural differences across countries and the uneven quality of environmental reporting. Additionally, because many sub-Saharan African countries allocate very limited resources to climate mitigation and CO_2-related management, population pressures translate more directly into rising emissions. This stands in contrast to the expectations of the Paris Agreement, where effective emissions management requires sustained investment in low-carbon technologies, waste systems, and environmental governance—areas where many countries in the region continue to face significant constraints.

This finding is in line with those of Lawal and Mukhtar (2019), which was conducted in Nigeria, as well as the results from a study conducted by Di Lavoro (2006) in OECD countries.

In terms of electricity production from renewable energy (EPRE), we found that this has a significant positive impact on environmental quality in sub-Saharan African countries. A recent study using heterogeneous macro-panel data analysis found that increasing the share of renewable energy in electricity production contributes to improved environmental quality, suggesting that renewable energy can help alleviate environmental degradation in sub-Saharan Africa (Bekele et al., 2024) .

In contrast, however, another study using the differentiated-generalised method of moments (GMM) found that while renewable energy consumption can reduce CO_2 emissions, its overall impact on environmental quality may not always be positive. Factors such as the type of renewable energy, the region's economic structure, and governance quality can influence the outcomes. For example, poor governance can negate the mitigating effect of renewable energy on CO_2 emissions (Wang et al., 2023).

In our study, we further found that the energy use per capita (EUPC) has a significant negative effect on CO_2 emission, while the energy imports (EI) as a percentage of total energy use has a significant positive influence on CO_2 emission in sub-Saharan African countries. This, according to Baum et. al. (2021), suggests that higher energy efficiency or cleaner energy use per capita can help decrease emissions, and reliance on imported energy, often from fossil fuels, contributes to higher emissions. Moreover, we found that literacy rate (LR) and secondary education (SSE) are the measures of human capital, and they have a positive and significant impact on CO_2 emission, in line with the findings of both Yao et. al. (2020) and Lawal and Mukhtar (2019). Nevertheless, the high R^2 values observed warrant caution and suggest the need for further robustness checks. Future studies could employ dynamic panel models or instrumental variable approaches to better address endogeneity and causality.

5. Conclusion and policy recommendations

The main aim of this paper is to test the Environmental Kuznets Curve (EKC) hypothesis for a sample of sub-Saharan African countries by examining how economic growth, GDP per capita, and energy consumption influence CO_2 emissions, which are used here as indicators of environmental quality. To achieve this objective, the paper adopts a multivariable framework that incorporates key energy and economic variables, along with control variables such as the GDP per capita (current USD), labour force and energy use per capita.

The results show that for every 1-unit increase in GDP per capita, environmental quality improves by approximately 2.88%, indicating that higher income levels are associated with lower CO_2 emissions. Likewise, GDP per capita squared reduces CO_2 emissions by about 0.0006% for every 1-unit rise, supporting the presence of the Environmental Kuznets Curve (EKC) in the region. In the pooled OLS analysis, the study finds that renewable energy sources—such as solar, biomass, hydro, geothermal, and wind—reduce CO_2 emissions, whereas non-renewable energy increases CO_2 emissions by 1.6% for every 1-unit rise in its use. The results further reveal that research and development (R&D) expenditure has a positive and significant effect on CO_2 emissions, meaning that a 1-unit increase in R&D spending is associated with higher emissions, likely due to limited investment in green technologies.

Regarding population size, the findings show that a 1-unit increase in population raises CO_2 emissions by 0.028%, reflecting the pressure that population growth places on waste generation, energy demand, and land use in sub-Saharan Africa. Electricity production from renewable energy (EPRE) has a positive and significant effect on environmental quality, indicating that for every 1-unit increase in EPRE, CO_2 emissions decrease. This reflects the growing role of solar, hydro, wind, and biomass in replacing carbon-intensive energy sources across the region. In contrast, energy use per capita (EUPC) has a negative and significant effect on environmental quality, meaning that a 1-unit rise in EUPC increases CO_2 emissions. This is expected because most households and firms in sub-Saharan Africa still rely heavily on fossil fuels, diesel generators, charcoal, and inefficient biomass for energy.

Similarly, energy imports (EI) as a share of total energy use increase CO_2 emissions, with each 1-unit rise in EI associated with higher emissions. Imported energy in the region is often petroleum-based, reflecting dependence on carbon-intensive fuels due to limited domestic refining and electricity generation capacity.

Moreover, the study finds that literacy rate (LR) and secondary school enrolment (SSE)—used as measures of human capital—increase CO_2 emissions for every 1-unit rise, suggesting that improvements in education currently correlate with economic activities that are still carbon-intensive. On the economic side, R&D expenditure has a negative effect on GDP per capita, while renewable energy production increases GDP per capita, and energy use per capita reduces GDP per capita. Additionally, literacy rate and secondary education both reduce the growth rate of GDP per capita, indicating structural challenges in translating human capital improvements into economic productivity.

Based on our results, we recommend that policymakers in sub-Saharan Africa:

- Promote renewable energy adoption through targeted incentives and sustained infrastructure investment, as the results show that greater electricity production from renewable sources significantly improves environmental quality and reduces CO_2 emissions across sub-Saharan African countries.
- Strengthen education systems and expand R&D capacity to support the development of environmentally sustainable technologies, recognising that current R&D spending is associated with higher emissions due to limited focus on green innovation, while improvements in human capital still correlate with carbon-intensive economic activities.
- Implement population-sensitive policies and integrated urban planning strategies that support low-carbon development, given that population growth is found to increase CO_2 emissions through rising energy demand, waste generation, and pressure on existing infrastructure.

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Authors' contributions Ebrima K. Ceesay: Conceptualisation, data curation, methodology, econometric modelling, formal analysis, interpretation of results, preparation of the original manuscript draft and overall writing, review and editing. Matarr Njie: Language review, proofreading and correction of grammatical and stylistic issues. Emmanuel Igbinoba: Provision of data and support with data acquisition. Etse Yawo Dzakpa: Literature review and synthesis of related studies. Mohamed Ben Omar Ndiaye: Provision of data, supervision of the research process and guidance throughout the development of the manuscript. Amie M. Jobe: Preparation and formatting of tables. Amadou Cham: Preparation and formatting of tables. Ebrima B. Jallow: Language review and proofreading. Cherno Jallow: Language review and proofreading. Lamin B. Jammeh: Language review and proofreading. All authors read and approved the final version of the manuscript.

Data Availability The datasets for this study can be found in the [Google Drive] [Recent - Google Drive or Home - Dropbox] from Global economy, world economy | TheGlobalEconomy.com. Please see the "Availability of data" section of Materials and data policies in the Author guidelines for more details.

Declarations

Competing Interests The authors declare no competing interests.

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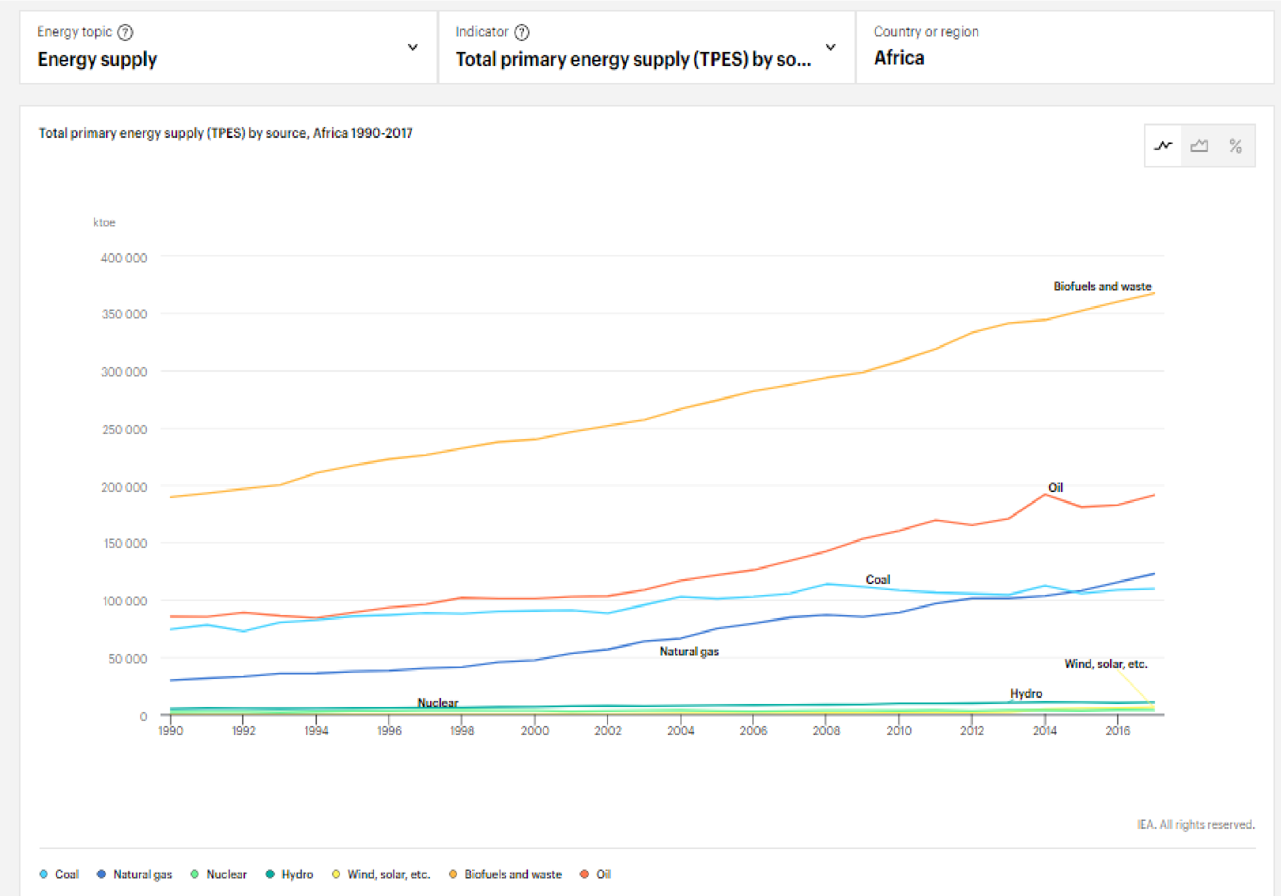
Appendix


Energy topic
Energy supply
Indicator
Total primary energy supply (TPES) by so...
Country or region
Africa
Total primary energy supply (TPES) by source, Africa 1990-2017
ktoe
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350 000
300 000
250 000
200 000
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100 000
50 000
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1990
1992
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2000
2002
2004
2006
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2014
2016
Biofuels and waste
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