EDUCATION AND ENVIRONMENTAL EMISSIONS-INNOVATION NEXUS: EVIDENCE FROM SUB-SAHARAN AFRICA

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ABSTRACT

This study explores the moderating impact of education on innovation and environmental emissions. The empirical analysis was conducted for 41 sub-Saharan African countries for the period 2000 to 2022, employing the cross-sectional autoregressive distributed lag estimation technique. From the estimation techniques, it is confirmed that education is a significant variable that moderates the impact of innovation on emissions in both the short and long run. Additionally, this study computes the threshold and marginal effect of education on innovation's impact on emissions, signifying that the impact of innovation on emissions is conditional upon the education level. Thus, policymakers in sub-Saharan African countries must emphasize education as a key instrument to strengthen the beneficial impact of innovation on environmental quality and foster more sustainable development.

Keywords: *Education; Environmental emissions; Innovation; sub-Saharan Africa*

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1. INTRODUCTION

Theoretically, it is widely acknowledged that the Environmental Kuznets Curve (EKC) postulates a relationship between environmental emissions and economic growth. As revealed by Grossman and Krueger (1995), in the early stages of economic growth, emission levels rise and environmental quality declines due to increased industrialization, energy consumption, and reliance on non-renewable resources. This phase is often characterized by a focus on economic development over

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environmental sustainability, leading to higher pollution levels and resource depletion. Later, after economic growth reaches a certain threshold point, emission levels decline as environmentally friendly investments, such as clean technologies, green manufacturing, and energy efficiency, are made. These investments promote sustainable practices, improve environmental quality, and reduce emission levels. Empirically, the presence of the EKC has been validated by a number of past studies, including Irokanulo and Beton Kalmaz (2024), Mohamed et al. (2024), Boluk and Karaman (2024), Han and Lin (2025) and others. The logic of these researchers suggests that emissions decline as rising incomes are invested in environmentally friendly technologies and innovations, minimizing environmental impact.

Despite the validation of the EKC in past studies, exploring the dynamics of the EKC in the context of innovation remains questionable, particularly in sub-Saharan African (SSA) countries. A recent report from the World Bank (2024) highlights that SSA countries have made significant digital transformations across the region, building the foundation for vibrant, safe, and inclusive digital societies and economies. These innovative advancements include internet connectivity and accessibility, digital payment systems, and digital development projects in agriculture, financial services, and manufacturing, ensuring the needs of the people are met and supporting the goal of sustainable economic development. Such innovations not only drive economic growth, job creation, and inclusion but also contribute to environmental sustainability. For example, advanced technologies and innovations enable more efficient resource use, expand clean and renewable energy resources, and improve waste management, thereby supporting good environmental quality and controlling emissions.

However, the reality remains far behind, as SSA countries continue to suffer from rising emissions and climate change issues. Given SSA countries' exposure to climate change, this disproportionally harms ecosystems, food security, and exacerbates the threat of conflict over deteriorating resources (World Meteorological Organization, 2023). As seen in Figure 1, rising economic growth levels and increased innovation in SSA have yet to result in a decrease in emissions, even after reaching turning points that are generally predicted to drive environmental improvements. This explains that innovations, along with economic growth, are not sufficient to lead to environmental awareness and improvement without the complementary factor of education. Education plays a critical role in equipping people with the knowledge and skills needed to adopt and utilize innovative technological advancements sustainably, in ways that enhance environmental quality. Well-educated societies are better equipped and more empowered to adopt and leverage advancements in innovative technologies to address climate change and reduce emissions, while also advocating for and implementing policies aligned with environmental goals. Thus, integrating education with innovative technological advancements may assist SSA countries in realizing the real benefits offered by these technologies, specifically in maintaining sustainable economic growth and environmental sustainability.

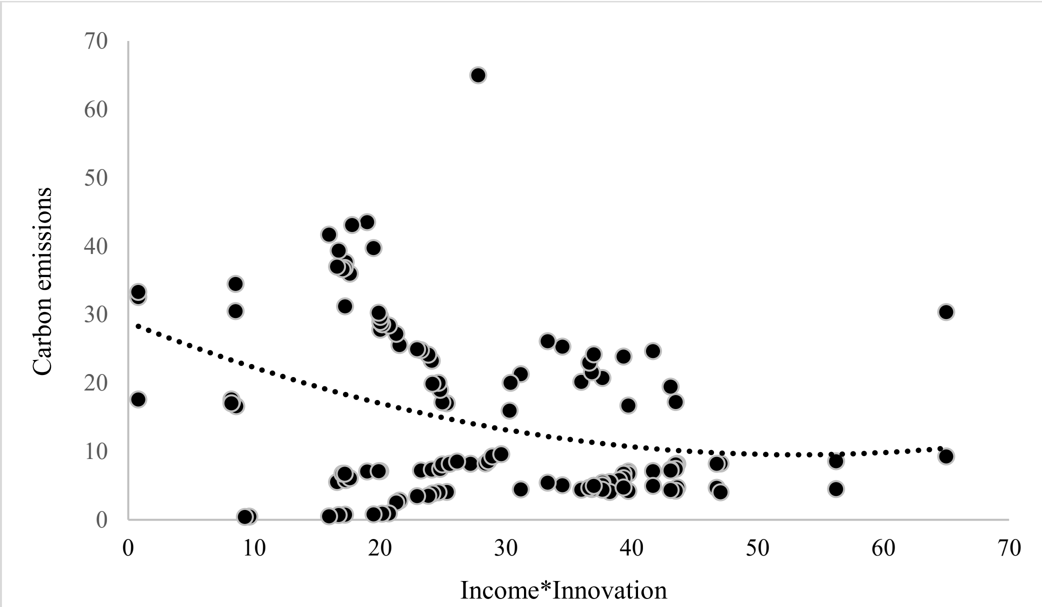

Figure 1: The linkages innovation on income-emissions nexus in Sub-Saharan Africa countries

Source: World bank (2024) & UNCTAD (2024)

Thus, the main objective of the article is to examine the moderating impact of education on the innovation-emissions nexus in SSA countries, underlining the critical need to discover pathways that link innovation, economic growth, and environmental sustainability. Therefore, the findings of this study will serve as an eye-opener for policymakers to understand the role of education in optimizing the effectiveness of innovative technologies in reducing emissions and supporting sustainable development in SSA countries.

The remaining sections of the article are organized as follows: Section 2 discusses past studies and the significance of the study, Section 3 presents the methodology and techniques employed, Section 4 interprets the results, and Section 5 highlights the conclusion and policy implications.

2. LITERATURE REVIEW

Studies on environmental emissions are extensive, investigating the linkages between emissions and variables such as income, trade, foreign direct investment, and renewable energy consumption. Yet this study discusses past studies on the selected variables to allow a deeper understanding of the specific factors influencing environmental emissions.

Income has become a major concern among researchers, continuing to validate the presence of the EKC (Ahmad et al., 2021a; Fatima et al., 2021; Syed and Bouri, 2021; Shittu et al., 2021; Cai et al., 2023; Habiba et al., 2022; Bhowmik et al., 2022; Awan et al., 2023; Anwar et al., 2023; Irokanulo and Beton Kalmaz, 2024; Mohamed et al., 2024; Sun et al., 2024; Boluk and Karaman, 2024; Han and Lin, 2025). These studies confirmed the presence of the EKC hypothesis, which suggests that emissions rise in the early stages of increasing income and then decline after reaching a certain turning point. A reduction in emissions levels after a certain point reflects the adoption of environmentally friendly approaches such as clean technology, stricter environmental regulations, and renewable energy as income rises alongside the spread of industrialization. Contrarily, Sarkodie (2018), Alol and Donve (2021), Zeraibi et al. (2022), Djellouli et al. (2022), Massagony and Budiono (2023), Erdogan (2024), Şerifoğlu and Öge Güney (2024) and Wu et al. (2025) observed N-shaped, U-shaped, and monotonic relationships between environmental emissions and income. The N-shaped link between emissions and income indicates that emissions increase with income, decrease after a certain turning point, but increase again at higher income levels. In contrast, the U-shaped pattern describes the opposite of the inverted U-shape, where emissions decline with income initially but rise again as income increases further. Therefore, the linkage between income and environmental emissions remains inconclusive and requires further study to confirm the relationship between income and emissions in SSA countries.

In addition, Zhang and Zhou (2016), Demena and Afesorgbor (2020), Xie et al. (2020), Wang et al. (2021), Lin et al. (2022), Apergis et al. (2023), Lee and Zhao (2023), Iqbal et al. (2023), Mahmood et al. (2023), Ren et al. (2024), Dilanchiev et al. (2024) Ganda (2024) and others identified foreign direct investment as one of the determinants of environmental emissions. These studies explain the linkages between foreign direct investment and emissions using the theories of the pollution haven and pollution halo hypotheses. Zhang and Zhou (2016), Wang et al. (2021), Lin et al. (2022) and Yi et al. (2023) for china, Xie et al. (2020) for emerging countries, Iqbal et al. (2023) for BRICS, Mahmood et al. (2023) for MENA, Dilanchiev et al. (2024) for top remittance-receiving countries and Ganda (2024) for sub-Saharan Africa countries showed that an increase in foreign direct investment leads to economic growth but also exacerbates environmental degradation due to the rise of pollution-intensive industries. This positive relationship between foreign direct investment and emissions is associated with the pollution hypothesis. On the other hand, foreign direct investment improves environmental quality by contributing to clean technologies and environmentally friendly practices (Demena and Afesorgbor, 2020; Abid et al., 2022; Apergis et al., 2023; Ren et al., 2024). Advanced technologies and environmentally friendly practices transferred through FDI inflows to host countries improve environmental quality, reducing emission levels. Hence, findings from empirical studies highlight that the impact of foreign direct investment on environmental emissions is influenced by the nature of the inflows, including industrial structures, technology transfer, and environmental regulations in host countries. This underscores that foreign direct investment has a significant relationship with environmental emissions.

Renewable energy has received significant attention among scholars in determining the level of environmental emissions (Farhani and Shahbaz, 2014; Adams and Acheampong, 2019; Saidi and Omri, 2020; Lima et al., 2020; Wang et al., 2021; Rehman et al., 2022; Kuang et al., 2022; Raihan, 2023; Kwilinski et al., 2024; Shah et al., 2024; Idroes et al., 2024). Renewable energy sources such as biofuels, solar, wind, and hydroelectric power are defined as alternatives to fossil fuels and emit fewer emissions compared to non-renewable energy sources. Higher consumption of renewable energy significantly improves environmental quality by promoting the integration of renewable energy into heating, industrial processes, and transportation sectors. This, in turn, reduces emissions and environmental stress, minimizing environmental impacts. For example, recent studies conducted by Saidi and Omri (2020) for 15 major renewable energy-consuming countries, Lima et al. (2020) for Brazil, Wang et al. (2021) for Belt and Road countries, Kuang et al. (2022) for China, Raihan (2023) for Colombia, Shah et al. (2024)for G20 countries, Idroes et al. (2024) for Indonesia, which examined the impact of renewable energy on environmental emissions, revealed a negative impact on emission levels. Greater consumption of renewable energy sources compared to traditional fossil fuels mitigates environmental impact by reducing emissions. Conversely, Rehman et al. (2022), and Farhani and Shahbaz (2014) point out an insignificant impact of renewable energy on emissions due to the unstable availability and insufficient capacity of renewable energy to address environmental impacts. As a result, while the full impact of renewable energy remains debated, this study concludes that renewable energy has a significant effect on environmental emissions.

Innovation is widely seen as a key driver of economic development, increasing productivity by facilitating the efficient use of resources and opening new markets and opportunities. It also supports and promotes sustainability and long-term sustainable economic development that addresses global challenges such as climate change, fragility, and conflict. In this context, Zhang et al. (2017) for China, and Obobisa et al. (2022) for Africa, Manu et al. (2024) and Ganda (2024) for sub-Saharan Africa, Su and Moaniba (2017) for a panel of 70 countries, Kwakwa et al. (2023) for Ghana, Khattak et al. (2020) for BRICS, Erdoğan et al. (2020) for G20 countries, and Matenda et al. (2024) for South Africa examined the influence of innovation on environmental emissions and reported mixed impacts. For instance, Khattak et al. (2020), Erdoğan et al. (2020), Kwakwa et al. (2023), Manu et al. (2024), Ganda (2024), and Matenda et al. (2024) assert that innovation curbing environmental emissions by facilitating the development of advanced technologies in economic activities via transportation, industrial and energy sectors. These advancements not only promote economic growth but also lower the environmental impacts. Besides that, advanced innovation in energy sector increases the availability of renewable energy technologies such as wind and solar power enhance energy efficiency and enables carbon captures significantly lessen emissions and improve environmental quality.

Nonetheless, Demir et al. (2020) for Turkey, Ahmad et al. (2021b) for OECD, and Villanthenkodath and Mahalik (2022) for India, discovered that innovation increases rather than reduces emissions. Advanced technological advancements drive greater industrial expansion and economic development, which lag behind concerns about sustainability and result in increased energy and fossil fuel consumption. This escalates emission levels and pollutes the quality of the environment. In certain situations, even when innovations improve efficiency and lower costs, it may inadvertently raise emissions through overconsumption of resources and higher production volumes. Similarly, a lack of expertise and skills in implementing or integrating innovative technological advances reduces consciousness of their environmental impact, placing economic gains and productivity ahead of environmental considerations. Thus, based on a consideration of previous studies on innovation and emissions, it is suggested that innovation has the potential to improve environmental quality by lowering environmental emissions. However, due to a lack of consciousness about the environmental impact of innovation, it can sometimes pollute the environment.

In this context, education may play a significant role in addressing the disparity by raising environmental awareness, providing the skills needed to implement sustainable innovations, and promoting a better understanding of the long-term environmental consequences of technological advancements. Integrating education into the innovation process can help to limit the detrimental impacts of innovation on the environment while maximizing its potential to improve environmental quality. As a result, this study aims to investigate the moderating impact of education in the innovation-emission nexus, offering new insights into how education might enhance the effectiveness of innovation in improving environmental quality, particularly in sub-Saharan African countries. Such findings have significant implications for policymakers, educators, and development practitioners seeking to integrate technological innovations with environmental goals, providing a strong foundation for reducing emissions while supporting sustainable economic growth.

3. DATA AND METHODOLOGY

3.1 Data

This study focused on 41 sub-Saharan African countries, namely Benin, Kenya, Sierra Leone, Burundi, Burkina Faso, Madagascar, Seychelles, Central Africa Republic, Botswana, Mali, Togo, Congo DR, Cote d'Ivoire, Mozambique, Tanzania, Comoros, Cameroon, Mauritius, Uganda, Mauritania, Congo, Republic, Namibia, South Africa, Equatorial Guinea, Cabo Verde, Niger, Malawi, Chad, Gabon, Nigeria, Ethiopia, Zambia, Ghana, Rwanda, Lesotho, Guinea-Bissau, Sudan, Guinea, The Gambia, Senegal, Angola. Data for income, foreign direct investment, renewable energy, innovation, and environmental emissions were collected from the World Bank Indicators and UNCTAD for the period 2000 to 2022. Additionally, the details and measurements for each key dependent and independent variable are presented in Table 1, along with their sources.

Table 1: Data sources

Variables	Symbol	Measurement	Sources
Environmental emissions	*CO2*	CO2 emissions (metric tons per capita)	
Income	*Y*	GDP per capita in constant	
Foreign direct investment	*FDI*	Foreign direct investment inflows (percentage of GDP)	World Bank (2024)
Renewable energy	*RE*	Renewable energy consumption of final energy use	
Education	*EDU*	Gross secondary enrolment ratio.	
Innovation	*INO*	Frontier technology readiness index (index)	UNCTAD (2024)

3.2 Methodology

To derive the estimation model, this study employs the EKC hypothesis as a baseline, which postulates the nonlinear linkages between income and environmental emissions. As explained in past studies, in the early stages of income growth, emissions increase until a certain turning point, after which emissions levels decline as income continues to rise. This is represented in the following equation *(Eq. (1))* as follows:

$$lnCO_{2it} = \alpha_0 + ln\beta_1 Y_{it} + ln\beta_2 Y_{it}^2 + \varepsilon_{it} \tag{1}$$

Where Y is income and Y^2 is income squared. By extension, *Eq. (1)* is extended to include additional variables highlighted in the previous section, foreign direct investment (*FDI*) (Mahmood et al., 2023; Ren et al., 2024; Dilanchiev et al., 2024; Ganda, 2024), renewable energy (*RE*) (Kuang et al., 2022; Raihan, 2023; Kwilinski et al., 2024; Shah et al., 2024; Idroes et al., 2024), and innovation (*INO*) (Khattak et al., 2020; Erdoğan et al., 2020; Kwakwa et al., 2023; Ganda, 2024) as formulated in *Eq. (2)*

$$lnCO_{2it} = \alpha_0 + ln\beta_1 Y_{it} + ln\beta_2 Y_{it}^2 + ln\beta_3 FDI_{it} + ln\beta_4 RE_{it} + ln\beta_5 INO_{it} + \varepsilon_{it} \tag{2}$$

Subsequently, the model is completed by incorporating the core variable of interaction term (*EDU*INO*), examining the moderating role of education (*EDU*) in the relationship between innovation and environmental emissions, as depicted in *Eq. (3),*

$$\begin{aligned} lnCO_{2it} = \alpha_0 + ln\beta_1 Y_{it} + ln\beta_2 Y_{it}^2 + ln\beta_3 FDI_{it} + ln\beta_4 RE_{it} + ln\beta_5 INO_{it} + ln\beta_6 EDU_{it} \\ + ln\beta_7 (EDU * INO)_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

Parameters $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, and\ \beta_8$ are the coefficients of the regressors, the prefix ln is the natural logarithm, ε is the error term and $i\ and\ t$ represent the time period and cross-sections, respectively. in addition, this study computes the marginal effects to discover the moderating impact of education on the innovation-environmental emission nexus. Computing the marginal effect to assess the partial derivative of environmental emissions with respect to innovation, considering education, as presented in *Eq. (4)*

$$\frac{\partial CO2_{it}}{\partial INO_{it}} = \beta_5 + \beta_7 EDU_{it} \tag{4}$$

In terms of estimation technique, this study employs Cross-Sectional-Autoregressive Distributive Lag (CS-ARDL) to evaluate the short- and long-run impact of education on the nexus of innovation and environmental emissions. There are five steps to run the CSARDL estimation technique, as follows:

i. Cross-sectional dependence (CD)

CD serves to analyze the variation in slope parameters caused by cross-sectional dependence, a common problem in panel time series analysis (Ahmad et al., 2022). CD can arise as a result of unobserved shocks, leading to biased results. Thus, Pesaran's approach (Pesaran, 2004) was used to address this issue, and the equation is provided as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \; (\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \tag{5}$$

Where $\hat{\rho}_{ij}^{2}$ represents the pair-wise correlation, and N and T are for cross-section and time, respectively.

ii. Slope homogeneity

After examining cross-sectional dependence, slope homogeneity was tested to assess whether the slopes were homogeneous due to variations in a country's demography, economy, and social structure. Pesaran et al. (2008) used *Eq. (6)* to test slope homogeneity, as stated below:

$$\widetilde{\Delta_{SH}} = (N)^{\frac{1}{2}}(2K)^{-\frac{1}{2}}(\frac{1}{2}\tilde{S} - k)$$

$$\widetilde{\Delta_{ASH}} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}(\frac{1}{N}\tilde{S} - k) \tag{6}$$

Where $\widetilde{\Delta_{SH}}$ *is delta tilde and* $\widetilde{\Delta_{ASH}}$ is delta tilde adjusted.

iii. Unit root test

The panel stationarity and order of integration will be examined next using the cross-sectional augmented Dickey-Fuller (CADF) and Im-Pesaran-Shin (CIPS) unit root tests (Pesaran, 2007). These tests are required to check the integrating properties of the variables, that is, $\Delta CA_{i,t} = \varphi_i + \varphi_i Z_{i,t-1} + \varphi_i \overline{CA_{t-1}} + \sum_{l=0}^{\rho} \varphi_{il} \Delta \overline{CA_{t-1}} + \sum_{l=0}^{\rho} \varphi_{il} \Delta \overline{CA_{\iota,t-1}} + \mu_{it}$, where $\overline{CA_{t-1}}$ *and* $\Delta\overline{CA_{t-1}}$ are the cross-section averages. The CIPS test statistics are expressed as

$$\widehat{CIPS} = \frac{1}{N}\sum_{i=1}^{n} CDF_i \tag{7}$$

iv. Panel cointegration test

Once the stationarity of the variables has been validated, the panel cointegration test is used to investigate the long run cointegration relationships among the variables using the Westerlund (2007) panel cointegration test. The Westerlund (2007) panel cointegration test is particularly suitable for addressing the presence of cross-sectional dependence and heterogeneity.

$$\alpha_i(L)\Delta y_{it} = \delta_{1i} + \delta_{2i}t + \alpha_i(y_{it-1} - \beta_i' x_{it-1} + \lambda_i(L)' v_{it} + e_{it} \tag{8}$$

Where α_i is the cointegration vector between y and x and β_i is an error correction coefficient. It can be described empirically as follows

$$G_t = \frac{1}{N}\sum_{i=1}^{N} \frac{\alpha_i'}{SE(\alpha_i')} \;;\quad G_\alpha = \frac{1}{N}\sum_{i=1}^{N} \frac{T\alpha_i'}{\alpha_i'(1)};\quad P_t = \frac{\alpha'}{SE(\alpha')};\quad \alpha' = \frac{P_\alpha}{T} \tag{9}$$

Where $\alpha' = \frac{P_\alpha}{T}$ is the short-term imbalance in the proportion of error that needs to be corrected each year.

v. CS-ARDL

Finally, the Cross-Sectional-Autoregressive Distributed Lags (CS-ARDL) model was used to estimate long- and short-run coefficients. Further, CS-ARDL is appropriate for non-stationarity and endogeneity issues. As a result, the CS-ARDL equation is presented below:

$$\Delta CO2_{i,t} = \varphi_i + \sum_{j=1}^{p} \varphi_{it}\Delta CO2_{i,t-j} + \sum_{j=0}^{p} \varphi_{ij}' X_{i,t-j} + \sum_{j=0}^{p} \varphi_{ij}' \overline{Z_{t-j}} + \varepsilon_{i,t} \tag{10}$$

X is the set of explanatory variables represented and $\overline{Z}_t = (\Delta\overline{CO2_t}, \overline{AEV_t'})'$ defines as the cross-section averages.

4. RESULTS AND DISCUSSION

Before starting the five steps of CS-ARDL, this study began with descriptive statistics and correlation analysis, and the results are displayed in Table 2. Table 2 reports the mean, minimum, maximum, and standard deviation values for all the variables employed in this study. Among the variables, the highest mean value for environmental emissions is 3.691, while the minimum and maximum values are 1.791 and 6.433, respectively. For innovation, the mean and maximum are 0.024 and 1.932, respectively, and the lowest mean value is represented by education at 0.011. The standard deviation essentially shows the extent of deviation from the mean value, revealing that education and foreign direct investment exhibit relatively low variation compared to other variables. Additionally, the low variability observed in *lnFDI* and *lnEDU* is a concern, particularly for *lnEDU*, which exhibits a very small standard deviation (0.011). Looking at the correlation analysis, there is a positive correlation between foreign direct investment and innovation with environmental emissions (see Table 3). Based on Table 3, the correlation coefficients are generally weak (absolute values below 0.2), indicating the absence of strong pairwise linear relationships among the variables. This suggests that simple bivariate associations may be insufficient; therefore, more advanced regression techniques are employed below to uncover underlying relationships.

Table 2: Summary of the variables

Variable	Mean	Std. Dev.	Min	Max
$lnCO_2$	3.691	0.113	1.791	6.433
lnY	2.961	1.258	0.916	3.898
lnFDI	1.787	0.092	0.585	0.919
lnRE	12.150	1.297	9.378	13.723
lnINO	0.024	1.202	-2.303	1.932
lnEDU	4.723	0.011	2.708	5.742

Table 3: Correlation analysis

	$lnCO_2$	*lnY*	*lnFDI*	*lnRE*	*lnINO*	*lnEDU*
$lnCO_2$	1.000					
lnY	-0.050	1.000				
lnFDI	0.171	0.089	1.000			
lnRE	-0.083	-0.069	-0.010	1.000		
lnINO	0.015	0.191	0.086	-0.040	1.000	
lnEDU	-0.070	-0.043	-0.073	0.082	-0.093	1.000

Now, the analysis begins with the first step of cross-sectional dependence (CD) to analyze the variation in slope parameters, with the results shown in Table 4. At the 1% significance level, the CD test rejects the null hypothesis of no cross-sectional dependence, confirming its presence. This suggests that a shock in one country will influence other countries, indicating a high level of interdependence among them.

Table 4: Cross-sectional Dependency Test (CD Test)

Variable	***CD-Statistics***	***P-value***
$lnCO_2$	52.70***	0.00
lnY	47.90***	0.00
lnY^2	62.60***	0.00
lnFDI	17.27***	0.00
lnRE	54.20***	0.00
lnINO	12.39***	0.00
lnEDU	33.32***	0.00

Note: Asterisks *** denote 1% levels of significance.

Then, we proceed with the slope homogeneity test. The output is displayed in Table 5, highlighting heterogeneity by rejecting the null hypothesis of no heterogeneity. The values of delta and adjusted delta are significant at the one percent level, confirming the presence of heterogeneity issues among the variables.

Table 5: Slope Homogeneity Test

Slope homogeneity Test	**Δ statistic**	***P-value***
$\widetilde{\Delta_{test}}$	8.311***	0.000
$\Delta_{\widetilde{adj\ test}}$	89.097***	0.000

Note: Asterisks *** denote 1% levels of significance.

Table 6 shows the results of the unit root tests (CIPS and CADF) to assess the stationarity of the variables. The CIPS and CADF results indicate that all variables, except *lnINO*, are not stationary in their level form but become stationary *(I (1))* at the first difference. This represents the failure to reject the null hypothesis of a unit root at the level, and vice versa at the first difference. As a result, the variable *lnRE* has a unit root issue at the level, whereas the other variables become stationary at the first difference.

Table 6: Panel unit root tests

Variables	**CIPS Test**		**CADF Test**		**Decision**
	Level	*1st difference*	*Level*	*1st difference*	
$lnCO_2$	1.750	2.021***	3.971	7.441***	I (1)
lnY	2.433	7.159***	3.178	8.436***	I (1)
lnY^2	-1.065	-2.770***	-2.437	-5.083***	I (1)
lnFDI	0.733	1.396***	0.890	1.1204***	I (1)
lnRE	3.593	4.254***	2.913	4.190***	I (1)
lnINO	0.134***	1.084***	-	-	I (0)
lnEDU	-1.160	-3.415***	-5.793	-8.272***	I (1)

Note: *** refers to statistical significance at the 1% levels, respectively

Further, this study proceeds to the Westerlund (2007) panel cointegration test to explore the cointegration among the variables. As shown in Table 7, the test statistics G_t, G_a, P_t, and P_a are significant at the 1 percent level, confirming the long-term relationship among the variables of income, renewable energy, education, foreign direct investment, innovation, and environmental emissions.

Table 7: Westerlund Cointegration

Statistics	G_t	G_α	P_t	α'
	5.552***	4.708***	6.912***	2.864***
	[0.005]	[0.000]	[0.000]	[0.002]

Note: Asterisks *** denote 1% levels of significance, respectively. [ ] contains the p-value

Based on the preliminary diagnostic tests, the Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) model is employed to examine both the short- and long-run relationships among the variables. The cross-sectional dependency test results (Table 4) indicate significant cross-sectional dependence across the panel, while the slope homogeneity test (Table 5) confirms the presence of heterogeneous slope coefficients. Furthermore, the panel unit root tests (Table 6) show that the variables are integrated of mixed orders, comprising both I (0) and I(1) processes. Given these data characteristics, the CS-ARDL approach is particularly suitable, as it accounts for cross-sectional dependence, slope heterogeneity, and mixed integration orders, while allowing for consistent estimation of both short- and long-run effects.

Table 8 displays the CS-ARDL regression results to establish the relationship between the dependent and independent variables in the short and long run. In the short run, the results suggest that all variables, including the interaction term (*lnEDU*lnINO*), are significant. The coefficient values for income and income squared are 0.224and -0.392, respectively, which are significant at the 5% level, confirming the presence of the EKC hypothesis. This indicates an inverted U-shaped relationship between income and environmental emissions in SSA countries. Foreign direct investment and innovation had coefficient values of 0.063 and 0.177, respectively, indicating a positive link with environmental emissions. As demonstrated by Xie et al. (2020), Iqbal et al. (2023), Mahmood et al. (2023), Dilanchiev et al. (2024), increased *lnFDI* inflows impede environmental quality due to weak environmental regulations, which are most likely relevant in developing countries. This, in turn, leads to increased industrial activity in the manufacturing, energy, and mining sectors, resulting in high levels of emissions. In addition, renewable energy has a significant negative relationship with environmental emissions, with a coefficient value of -0.042. A one percent increase in renewable energy consumption reduces emissions by 0.042 percent, significant at the one percent level. An increase in the consumption of renewable energy sources like wind, solar, and biodiesel tends to reduce reliance on fossil fuels, which in turn lowers the amount of emissions produced.

Table 8: Results of CS-ARDL

Variables	Short-run Impact	
	Coefficient	**p-value**
ΔlnY	0.224***	0.018
ΔlnY^2	-0.392**	0.034
ΔlnFDI	0.063**	0.052
ΔlnRE	-0.042*	0.066
ΔlnINO	0.177*	0.063
ΔlnEDU	0.370***	0.008
*ΔlnINO*lnEDU*	0.356**	0.030
ECM (-1)	-0.519***	0.012
	Long-run Impact	
lnY	0.046	0.040
lnY^2	-0.744***	0.000
lnFDI	-0.471***	0.003
lnRE	-0.029**	0.029
lnINO	0.023**	0.046
lnEDU	-0.959***	0.000
*lnINO*lnEDU*	-0.355**	0.019

Note: Asterisks *, ** and*** denote 10%, 5% and 1% levels of significance, respectively. () contains the P-value.

The interaction term (lnINO*lnEDU) of Table 8, is positive and significant, indicating that innovation amplified by education leads to higher emissions in the short run. In contrast to the short run, the interaction becomes negative, indicating that when education complements innovation, emissions decrease in the long run, a synergy effect. The short-run result is somewhat unexpected and may indicate that education is initially unable to moderate the environmental impact of innovation. This could be attributed to inadequate resources and policy support, structural rigidities within education systems, and the time lag required for educational outcomes to translate into cleaner and more sustainable innovation practices. For example, structural change lags because transforming educational outputs into practical, sustainable practices takes time. In regions such as SSA countries, education systems frequently prioritize economic productivity over environmental sustainability, emphasizing skills that drive immediate economic growth rather than cultivating long-term environmental awareness. Additionally, limited resources and regulatory constraints impede the adoption of sustainability-focused curricula, diminishing education's effectiveness in mitigating the environmental impact of innovation. As a result, these factors may limit education's potential to serve as a significant moderator in the short run.

Furthermore, the error correction term (*ECT*) indicates the speed of adjustment from the short to the long run, with a significant negative value. This depicts the presence of long-term equilibrium, with a 52 percent rate of convergence. Looking at the long-run impacts, income and income squared confirm the EKC hypothesis at the five percent significance level. The level of emissions rises with increases in income until a certain point, then declines as income growth facilitates environmentally friendly approaches such as clean energy and technologies and strengthens environmental regulations. The turning point is 1.017, demonstrating that rising income becomes a driver of environmental sustainability, improving environmental quality and lowering emissions levels beyond this threshold. Contrary to Alol and Donve (2021), Zeraibi et al. (2022), Djellouli et al. (2022), Massagony and Budiono (2023), and Erdogan (2024), this study supports the inverted U-shaped relationship between income and environmental emissions in SSA countries.

It is observed that foreign direct investment is responsible for decreasing emissions at the 1 percent significance level. This means that a one percent increase in *FDI* inflows will decrease emissions by 0.471 percent in the long run. Surprisingly, the impact of FDI contrasts with the short-run impact, where FDI increased emissions instead of reducing them in the long run. The contrasting impact of FDI in the long run can be attributed to FDI inflows enabling the transfer of more efficient and clean technologies over time. This offers long-term benefits of FDI toward environmental quality, aligning with the pollution halo hypothesis (Abid et al., 2022; Apergis et al., 2023; Ren et al., 2024).

Renewable energy reveals a significant negative impact on environmental emissions, as indicated in the short run. The coefficient value is -0.029 and significant at the 5 percent level, suggesting that a one percent increase in the consumption of renewable energy leads to a 0.029percent reduction in emissions levels. The coefficient value reflects a significant reduction in emissions, demonstrating the effectiveness of renewable energy in improving environmental quality and encouraging sustainable development. The negative linkages between renewable energy and emissions align with the findings of scholars such as Kuang et al. (2022), Raihan (2023), Kwilinski et al. (2024), Shah et al., and Idroes et al. (2024) who reported that renewable energy improves environmental quality. Thus, renewable energy decreases reliance on carbon-intensive sources, which are the leading contributors to emissions.

Moving to the core variable (*lnEDU*lnINO)* of the study, the long-run estimations specify that the interaction term has a significant negative relationship with environmental emissions in SSA countries. The coefficient of the interaction term is -0.355 and significant at the 5 percent level, validating the intuition that education moderates the adverse impact of innovation on environmental emissions. The significant negative coefficient indicates that the relationship between innovation and environmental emissions depends on the degree of education in SSA countries. In simple terms, the negative effect of innovation may disappear as a country's education level rises. Education improves a country's ability to effectively adopt, adapt, and implement innovative technologies that align with sustainable practices. For example, a more educated workforce is better equipped to recognize the environmental consequences of innovation and prioritize cleaner, more efficient technologies. Furthermore, in the context of SSA countries, where innovation is often associated with rapid industrialization and technological adoption, education serves as a moderating factor by ensuring that such innovations are not detrimental to environmental quality. It guides innovation toward improving environmental quality and reducing pollution.

Table 9: Marginal Effect and Threshold

Statistics	Low-income
Mean	-0.590
Min	0.125
Max	-1.204
Threshold	1.067

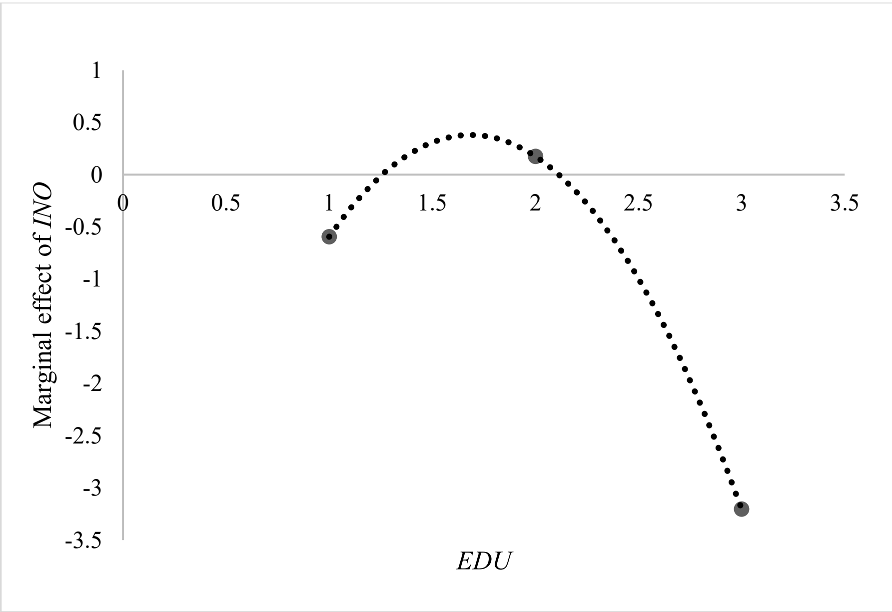

Figure 2: The marginal effect of INO on CO2, conditional upon EDU

Moreover, this study computed the threshold values to show the minimum level that SSA countries need to achieve to transform the adverse effects of innovation on emissions into beneficial outcomes. Table 9 displays the threshold value for the interaction terms, implying that innovation enhances environmental quality when education achieves a minimum improvement level of 1.067 percent. Hence, this again reveals that the adverse impact of innovation is not unconditional but is likely to depend upon the enhancement of education levels. Additionally, this study computes the marginal effects of changes in emissions levels due to changes in innovation. Table 9 also illustrates that innovation and education are significantly beneficial at mean and maximum levels, exhibiting values of 2.414 percent and 11.179 percent, respectively. In other words, the estimated effect of innovation on environmental emissions is mitigated at the mean and maximum levels of education (see Figure 2). For example, in SSA countries, it indicates that a 1-unit increase in innovation leads to a reduction of 0.790 percent in environmental emissions when evaluated at the mean level of education. Therefore, this highlights that as the level of education improves, innovation can enhance environmental quality by lowering emissions.

5. CONCLUSION

This study mainly examines the moderating impact of education on the innovation–environmental emissions nexus in sub-Saharan African countries. Using data from the period 2000 to 2022, this study employs the Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) estimation technique to determine the moderating role of education. The CS-ARDL estimation results confirm the existence of the Environmental Kuznets Curve (EKC) hypothesis in sub-Saharan African countries in both the short and long run. This implies that, after a certain threshold, rising income levels contribute to reducing environmental emissions in sub-Saharan African countries. Other control variables, such as foreign direct investment and renewable energy, revealed significant positive and negative impacts on environmental emissions, respectively. Additionally, this study achieves its main objective by confirming that education moderates the adverse impact of innovation on environmental emissions in sub-Saharan African countries. Specifically, education acts as a significant moderator in ensuring that innovation does not worsen environmental quality in the long run, although such moderating effects are insignificant in the short run. Overall, the findings of this study contribute directly to the achievement of several Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). By emphasizing the role of education in guiding innovation toward environmentally sustainable outcomes, this study highlights the importance of strengthening human capital and innovation capabilities to support long-term environmental sustainability and sustainable development in sub-Saharan African countries.

The significant impact of education in moderating the innovation-environmental emissions nexus suggests several policy implications for policymakers in reducing environmental emissions and maintaining environmental quality, particularly in sub-Saharan African countries. First, governments in sub-Saharan Africa should prioritize investments in education systems that incorporate environmental knowledge and sustainability into curricula. This includes teaching the skills required to embrace, adapt, and apply advanced innovations, along with promoting an understanding of sustainable development approaches. Second, sub-Saharan African countries should enhance science, technology, engineering, and mathematics (STEM) education. This will help build a trained workforce capable of driving innovation toward more sustainable practices. Training in environmental science and clean technology, for example, needs to be included to ensure that innovation aligns with improving environmental quality. Third, establishing technical and vocational education programs suited to the needs of green industries may help ensure that innovations developed in areas such as energy, agriculture, and manufacturing are implemented in a sustainable manner. As a result, the advancement of innovation tends to maximize the environmental benefits of innovation, encourage environmentally friendly approaches, and minimize the potential adverse effects on environmental quality.

CONFLICTS OF INTERESTS

Ethical Approval: Not applicable
Consent to Participate: Not applicable
Consent to Publish: Not applicable
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Competing Interests: No
Availability of data and materials: Data will be available upon request

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