

Investigating the dynamic relationship between human development and carbon dioxide emissions: Empirical analysis from African countries using the DCCE Approach

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Received: 02/01/2025

Accepted: 03/03/2025

Published: 25/05/2025

Abstract:

This study aims to investigate the dynamic relationship between human development and carbon dioxide emissions across 35 African countries from 1990 to 2022. By using advanced dynamic panel techniques, the DCCE approach, the findings demonstrate that the Human Development Index (HDI) significantly affects CO₂ emissions. The quadratic term of HDI positively affects carbon emissions, disproving the Environmental Kuznets Curve (EKC) hypothesis. In contrast, green energy consumption adversely impacts dioxide emissions, while globalization indicates no effect on atmospheric pollution in the studied context. The empirical analysis provides policy recommendations to improve environmental conditions in the studied countries.

Keywords: CO₂ emissions; human development; EKC hypothesis; African countries; DCCE.

JEL Classification Codes : Q56, C33, O13.

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1. INTRODUCTION

Climate change is a crucial and critical environmental challenge threatening sustainable development (Abidoye & Odusola, 2015; Awosusi & al., 2022; Onofrei & al., 2022; Azam & al., 2022). Recognized as a global emergency, it is also among the priorities of the Union Nations Sustainable Development Goals, particularly SDG 13, which aims to implement immediate measures to combat its impacts. Carbon dioxide (CO₂) emissions are among its primary causes, responsible for extreme weather events, including drought, heat waves, and flooding (Awosusi&al., 2022). These emissions, primarily attributed to human activities, have disproportionate environmental impacts, affecting ecosystems, economies, and populations, particularly in developing countries.

While Africa contributes minimally to global CO₂ emissions compared to developed countries (Pata&al., 2021), it is particularly vulnerable to their consequences (Ntarmah&al., 2020). This vulnerability stems from its geography, low-income levels, significant reliance on sectors vulnerable to climate conditions, and restricted ability to adapt to climate change (Abidoye & Odusola, 2015). Environmental challenges determine nations' socioeconomic progress (Awosusi & al., 2022). In Africa, where economic growth is accelerating, these issues are crucial and should remain a short-term priority. Indeed, between 1990 and 2021, Africa's average Human Development Index (HDI) increased from 0.54 to 0.69, reflecting progress in health, education, and living standards (UNDP, 2022). However, this progress has been accompanied by increased CO₂ emissions, rising from 61 to 239 Mt over the same period, illustrating concerning climate issues (World Bank, 2024). This trend reflects how countries' efforts to accelerate economic development often accompany significant environmental deterioration (Azam & al., 2022; Congregado & al., 2016).

This dynamic highlight complex challenges for African countries facing the need to reconcile human development with environmental sustainability (Awosusi &al., 2022). In other words, African countries must address a dual challenge: reducing poverty and improving quality of life while limiting environmental consequences and reducing carbon dioxide

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emissions. The literature offers varied perspectives on this relationship. A significant amount of research examines the link between economic growth and atmospheric pollution (Abidoye & Odusola, 2015; Adu & Denkyirah, 2019; Ntarmah & al., 2020; Congregado & al., 2016; Simionescu & al., 2021; Grossman & Krueger, 1991; Benamar & al., 2018; Benatek & Akriche, 2024), more recent research (Amponsah, 2023; Beyene, 2022; Tachega, & al., 2021) explores the specificities of the interconnection among human development and environmental pollution, highlighting rather contrasting results that demonstrate the ambiguity of this relationship.

The Environmental Kuznets Curve hypothesis (also known as EKC) is frequently employed to investigate these interactions (Kuznets, 1955). This theoretical framework posits that at low development levels, emissions increase with HDI. However, beyond a certain threshold, adopting sustainable environmental practices and advanced technologies leads to reduced emissions. However, researches by Soukiazis & al. (2019), Beyene (2022), Tachega & al. (2021), and Adu & Denkyirah (2019) emphasize that the validity of this hypothesis varies across regional contexts and income levels, particularly in Africa.

Despite these contributions, research has yet to explore, over an extended period, the dynamic relationship between HDI and carbon emissions in Africa while incorporating dimensions such as renewable energy consumption and economic globalization. In addressing this issue, this study looks to empirically investigate the impact of human development on CO₂ emissions in Africa between 1990 and 2022 while testing the EKC hypothesis in this specific context.

Problem statement: In light of this finding, the study investigates the dynamic relationship between human development and CO₂ emissions in select African economies. Specifically, it intends to answer the following questions: How does human development affect CO₂ emissions in African nations? This inquiry aligns with existing research on the factors driving environmental degradation in Africa (Abidoye & Odusola, 2015; Lawson, 2020; Ntarmah&al., 2020) while offering fresh insights into the specific

roles of human development, globalization, and renewable energy consumption.

Hypothesis: This research tests the EKC theory in Africa. It assumes that:

H1: An inverted U-shaped relationship exists between HDI and carbon dioxide emissions, indicating that environmental degradation is intense when HDI is low. As HDI progresses, technological innovations and the adoption of environmental policies reduce pollution.

This hypothesis will serve as a framework to guide econometric tests and refine the analysis based on the obtained results, thus allowing for interpretation adapted to regional specificities.

Research Objective: The main objective is to analyze the dynamic linkage between environmental degradation and human development in 35 African nations by integrating key variables, such as globalization and renewable energy uses, from 1990 to 2022.

The Importance of the Research: Previous research has examined how human development affects carbon emissions, but limited studies focus specifically on African countries. This study fills that gap by utilizing a balanced panel dataset and applying advanced heterogeneous panel methods. Unlike earlier empirical work, it applies the dynamic common correlated effect (DCCE) approach to address the panel data's heterogeneity and cross-sectional dependence (CSD).

The current research is pivotal as it provides fresh insights into how human development influences CO₂ emissions in select African countries, addressing critical socioeconomic challenges and variations across regions. The findings offer valuable guidance for policymakers, aiding in designing more inclusive and equitable public policies that promote balanced socioeconomic development while addressing environmental challenges.

Research Limits: This study is confined to 35 African countries (N=35) over the period 1990–2022 (T=33 years), with a specific focus on the theoretical framework of the EKC hypothesis.

Research methodology: To address the central question, a descriptive approach was adopted to analyze the theoretical framework of human development's effect on atmospheric pollution. In addition, an econometric

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approach was used to evaluate the dynamic link between human development and dioxide emissions in African nations.

Study content: The remainder of the research has three main sections. The second section provides a literature review of carbon emissions and human development. The next section outlines the empirical study's technique, detailing the sample, the variables analyzed, and the econometric model employed. The fourth section addresses the study's primary results. In conclusion, the key insights are summarized, the study's limitations are discussed, and recommendations for policymakers are provided.

2. Literature review

The link between economic development and environmental pollution has garnered increasing attention in environmental economics research. The EKC hypothesis, initiated by Simon Kuznets (1955), occupies a central position in these studies. This hypothesis postulates an inverted U-shaped interaction between human activities and increasing carbon emissions. It suggests that human activities influence pollution through three distinct effects. The expansion of economic activities, measured by income level, increases pollution (scale effect). Then, as countries modify their production strategies, the impact becomes a composition effect. Finally, a technical effect manifests at a particular development threshold, meaning that economic transformations and adopting modern environmentally friendly technologies enable a reduction in CO₂ emissions (Grossman & Krueger, 1991).

In his study conducted across 50 African countries between 2000 and 2019, Amponsah (2023) analyzes the link between HDI and atmosphere pollution within the EKC theory, using PCSE and FGLS econometric methods. The author validates the EKC hypothesis for countries with high HDI, where an inverted U-shaped relationship is observed. However, a simple U-shaped relationship is found for countries with medium and low HDI. Human development is a key factor in environmental degradation, with increasing impact according to the HDI level. Furthermore, Beyene (2022) questioned the generalization of the EKC in Africa, highlighting the varied impacts of urbanization, GDP, and trade openness on pollution.

Similarly, Adu and Denkyirah (2019) studied the EKC theory. They found that although emission reduction is possible at a low-income threshold in West African nations, the inverted U-shaped relationship fails to hold up over the long term. They recommend policies aimed at improving energy efficiency to limit environmental degradation.

Tachega & al. (2021) expanded this perspective by analyzing 54 African countries and categorizing economies by income level. Their study confirmed that EKC is reliable in economies with low and lower-middle incomes, with low thresholds for turning points. They also emphasize the importance of green energy, which reduces carbon emissions, while fossil fuels energy and agriculture have varying effects across income groups.

Lawson (2020) demonstrates that in 41 sub-Saharan African countries (1990-2013), CO₂ emissions primarily stem from combustible energy consumption, driven by improving living conditions rather than economic growth. The author emphasizes that efforts to improve living conditions (such as electricity access) lead to increased primary energy demand, which increases fossil fuel consumption and, consequently, greenhouse gas emissions. Ntarmah & al. (2020) reveal that growth reduces emissions in Central Africa, but credit access increases pollution in Central and East Africa while having the opposite effect in West Africa. For East Africa, the EKC is validated but rejected elsewhere, highlighting the need for adapted regional policies. These findings illuminate varied regional dynamics, necessitating differentiated policies to reconcile economic development and environmental sustainability.

Soukiazis, Proença, and Cerqueira (2019) examined the links between human development, green energy, and pollution in 28 OECD countries between 2004 and 2015. The authors concluded that development level, education, and total energy consumption determine environmental pollution factors. They also noted a non-linear relationship between countries' development levels and atmospheric pollution.

Adeleye al. (2023) studied the effect of globalization and fossil-fuel-based energy use on environmental pollution in seven South Asian countries using unbalanced panel data during 1980-2019. The authors

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validated the EKC hypothesis by showing that the energy-emissions relationship follows an inverted U-shape, while the globalization-emissions relationship indicates a U-shape. They observed distinct relationships across South Asian countries. In Pakistan, an inverted U-shaped EKC is validated for energy, while other countries exhibit a U-shaped interaction (Nepal and Sri Lanka). Finally, the study shows that globalization's effect on emissions is opposite to that of energy, with intensifying globalization exacerbating environmental pollution.

Pata & al. (2021) looked at the effect of economic globalization, green energy use, natural resource richness, and economic development on atmospheric pollution in the ten nations with the highest ecological footprint during 1992-2016. The authors demonstrated that the human capital EKC theory is invalid in the context of the studied nations and that increases in human capital and green energy use hurt the environment. Conversely, natural resource abundance deteriorates environmental quality, while globalization does not significantly affect environmental pressure. The authors concluded that human capital and green energy consumption are crucial for reducing pollution, but natural resource abundance must be managed cautiously to avoid environmental quality degradation.

Hacıımamoğlu & Cengiz (2024) investigated the effects of green energy use and revenues from natural resources on atmospheric pollution framework for using the quantile regression approach ASEAN-5 countries (1990-2018). The authors validated the EKC theory by confirming the inverse link between economic growth and pollution. They also indicated that renewable energy consumption reduces atmospheric pollution across all quantiles.

Van Tran & al. (2019) studied the interaction between human development, energy use, and pollution using the GMM (Generalized Method of Moments) in 90 countries (1990-2014). The authors observed a negative effect between human development and carbon emissions in developing countries but no association in developed countries. They also found no significant causal relationship between energy use and human capital. In testing the EKC hypothesis, they concluded it was invalid in the

studied context.

In conclusion, the analyzed studies reveal that the link between human development, globalization, green and fossil energy use, and environmental degradation is ambiguous, complex, and contextual. The EKC hypothesis is only partially validated in some cases, but it only applies sometimes and varies with development levels and regional specificities. Human capital and renewable energy consumption are crucial elements for improving environmental quality. However, natural resource abundance and globalization can exacerbate pollution, highlighting the need for strategies adapted to each nation.

3. Materials and methods

3.1 Study population and sample:

This study explores the dynamic relationship between human development on atmospheric pollution during the period 1990-2022 in 35 African countries, namely: Algeria, South Africa, Egypt, Niger, Senegal, Botswana, Democratic Republic of the Congo, Gabon, Togo, Côte d'Ivoire, Mali, Comoros, Tunisia, Republic of Congo, Eswatini, Ghana, Gambia, Guinea, Central African Republic, Lesotho, Libya, Malawi, Mauritania, Burundi, Mauritius, Mozambique, Zimbabwe, Sierra Leone, Tanzania, Morocco, Uganda, Benin, Kenya, Namibia and Zambia. The selection of countries depends on data availability. STATA 17 software is used for all estimation processes

This region's choice is justified by its geographical vulnerability, low-income levels, dependence on climate-sensitive sectors, limited adaptive capacities, and human development challenges, such as poverty reduction and quality of life improvement, all closely linked to CO₂ emissions.

3.2 Variables and sources:

Table 1 summarizes the various factors used and their respective sources. The dependent variable represents the total volume of carbon dioxide emissions, quantified in megatons of CO₂ equivalent.

The independent variables are:

- The Human Development Index (HDI)

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- Economic openness (GLOB) serves as an indicator for the level of economic globalization (as a % of GDP)

Renewable energy consumption as a proportion of total energy consumption (ENERGY) indicates energy transition and dedication to sustainable energy sources.

Table 1. Variable Descriptions and Sources

Variable	Explanation	Source
Carbon dioxide emissions (CO ₂)	Represents the total volume of carbon dioxide (CO ₂) emissions, expressed in megatonnes of CO ₂ equivalent.	World Development Indicators (WDI) (www.databank.worldbank.org)
Human Development Index (HDI)	Denotes a composite indicator of key human development achievements, encompassing life expectancy, education, and income levels.	United Nations Development Programme (UNDP) (www.hdr.undp.org)
Globalization (GLOB)	As reflected by merchandise trade (% of GDP)	WDI (www.databank.worldbank.org)
Renewable energy consumption (ENERGY)	Reflects the percentage of total energy consumption that comes from green sources.	WDI (www.databank.worldbank.org)

Source: Author

3.3 Study model:

To achieve the objective of this study, the model builds on the EKC approach, drawing inspiration from the work of Soukiazis & al. (2019). It incorporates a temporal dynamic by including the lagged dependent variable, enabling the capture of the evolving relationship between human development and dioxide emissions. This approach benefits from a relatively extended period of analysis, thereby enhancing the reliability of the results. Furthermore, the research highlights that green energy is a key

lever for lowering CO2 emissions, and the research suggests the following function for their evaluation:

$$CO2 = f(HDI, GLOB, ENERGY) \dots (1)$$

Where CO2 represents carbon dioxide emissions, HDI is the Human Development Index, GLOB denotes economic globalization, and ENERGY refers to renewable energy consumption. To test the validity of Kuznets' hypothesis (1955), we link HDI and its squared term to carbon dioxide emissions in equation (2). This approach examines the existence of an inverted U-shaped relationship between atmospheric pollution and human capital. Equation (2) below outlines the model used to assess the effect of the variables that explain the (CO2) emissions:

$$\ln CO2_t = \beta_0 + \beta_1 \ln CO2_{i,(t-1)} + \beta_2 \ln HDI_{i,(t)} + \beta_3 \ln HDI_{i,(t)}^2 + \beta_4 \ln GLOB_{i,(t)} + \beta_5 \ln ENERGY_{i,(t)} + u_{i,(t)} + \varepsilon_{i,(t)} \dots (2)$$

Where, $u_{i,t}$ represents the individual effect; ε_t denotes the error term, the indices "i" and "t" symbolize nation i and year t.

3.4 Methodology:

To estimate equation (2), using the DCCE approach is particularly suitable for addressing the cross-sectional dependence of errors and incorporating the lagged dependent variable (Chudik & Pesaran, 2015; Jan 2018). Cross-sectional dependencies may arise from standard shocks, such as oil price fluctuations or interdependencies from trade exchanges. Chudik and Pesaran (2015) emphasize that including a lag of cross-sectional averages, $p = \sqrt[3]{T} = \sqrt[3]{33} = 3.207$, enhances the consistency of the estimator. Before estimating the DCCE model, it is essential to first test for slope heterogeneity, the presence of CSD (Pesaran test), and unit roots.

3.5 Data description and Correlation matrix:

This study employs a balanced panel data for African nations from 1990 to 2022. The selected variables include carbon dioxide emissions (CO2), Human Development Index (HDI), globalization (GLOB), and renewable energy use (ENERGY). All data have been transformed into natural logarithms to facilitate interpreting the estimated coefficients in terms of elasticity of the dependent variable (CO2) and to minimize heteroscedasticity issues.

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Table 2. Descriptive Statistics

Variable		Mean	Standard deviation	Min	Max	Observations
CO2	overall	26.712	75.172	.1107	485.37	N = 1155
	between		74.384	.2315	402.74	n = 35
	within		16.466	-77.247	117.919	T = 33
HDI	overall	.5030	.128	.212	.806	N = 1155
	between		.11825	.30457	.75136	n = 35
	within		.05407	.37579	.65064	T = 33
GLOB	overall	53.609	27.438	7.8059	175.37	N = 1155
	between		24.343	25.396	129.288	n = 35
	within		13.291	13.402	133.072	T = 33
ENERGY	overall	59.803	30.564	.1	98.3	N = 1155
	between		30.271	.30696	96.439	n = 35
	within		6.5741	38.459	90.518	T = 33

Source: Author

Table 2 displays the descriptive data for this research variable, covering 35 countries (N = 35) over 33 years (T=33). The CO2 variable ranges from 0.11 to 485.37, with 26.71 at the mean and a 75.17 standard deviation. Between-unit variation (74.38) is significantly more significant than within-unit variation (16.47), reflecting substantial differences across entities. The HDI variable has 0.503 at the mean and 0.128 standard deviations, with between-unit variation (0.12) exceeding within-unit variation (0.054), indicating moderate unit differences. GLOB values range from 7.80 to 175.37, with 53.60 at mean and 27.43 standard deviation. ENERGY values vary between 0.1 and 98.3, with 59.80 at the mean and 30.56 standard deviations, showing significant dispersion. Most variation arises from between-unit differences (30.27), while within-unit variation is lower (6.57).

The results of the correlation matrix and the multicollinearity test are given in Table 3. The analysis reveals a significant and positive correlation between CO2 and HDI, whereas CO2 exhibits a negative and significant correlation with GLOB and ENERGY. No correlation coefficient exceeds

0.8, indicating the absence of severe multicollinearity among the variables, as Tabachnick & al. (2007) recommended.

Moreover, the Variance Inflation Factor (VIF) test results show values well below the critical threshold of 10, confirming the absence of significant multicollinearity among the explanatory variables (Hair & al., 2010). The mean VIF value, at 2.108, is significantly below this limit, further supporting the model's validity.

Table 3. Correlations matrix and VIF estimation

	(1)	(2)	(3)	(4)
(1) CO2	1.000			
(2) GLOB	-0.094*	1.000		
(3) HDI	0.424*	0.387*	1.000	
(4) ENERGY	-0.510*	-0.289*	-0.772*	1.000
VIF		1.177	2.67	2.477
1/VIF		.85	.375	.404

* $p < 0.01$

Source: Author

4. Empirical results

4.1 Homogeneity test :

To examine slope heterogeneity among the countries studied, we applied the Pesaran and Yamagata (2008) test. The evaluation is focused on the homogeneity of the slope coefficients. The results show that the p-value associated with the Delta test is below 0.05 (Table 4). This confirms the presence of slope heterogeneity across the units studied.

Table 4. Pesaran & Yamagata test for slope homogeneity

Pesaran & Yamagata test	Statistique value	P-value
Delta	39.539	0.000
adj	42.924	0.000

Source: Author

4.2 Pesaran CD test:

The Pesaran CD test was applied to evaluate CSD in the errors. The results presented in Table 5 illustrate that the p-value is below 5% for all variables, indicating significant CSD in the errors.

Table 5. Pesaran CD test analysis

Variable	CD-test	p-value
lnCO2	89.04***	0.000
lnGLOB	22.66***	0.000
lnHDI	115.570***	0.000
lnENERGY	48.31***	0.000

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: Author

4.3 Panel unitroot test:

Before testing for the presence of unit roots, it is essential to identify the optimal lag length by testing various specifications for each unit root test. The selection of lag p_y and le lag p_x is based on minimizing the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) for $p=q= 1,2, 3$ and 4. As shown in Table 6, the optimal lag length is 1 for the variables CO2, GLOB, and ENERGY, and 4 for HDI. These lag lengths will be used for the subsequent unit root tests.

Table 6. Optimum lag selection

	CO2		ENERGY		GLOB		HDI	
lag	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
1	-56.401	-47.797	-47.773	-39.169	9.3578	17.961	-179.201	-170.598
2	-53.644	-42.434	-41.000	-29.791	9.7006	20.910	-170.020	-158.810
3	-50.854	-37.181	-35.567	-21.894	11.978	25.651	-159.362	-145.689
4	-52.710	-36.723	-33.703	-17.716	9.0747	25.061	-148.598	-132.611

Source: Author

Given the presence of CSD in the errors, second-generation unit root tests (CADF-CIPS), are applied. The results presented in Table 7 indicate that all variables are I(0) or I(1), and no variable is I(2). We can estimate the DCCE model now.

Table 7. CADF and CIPS Unitroot test

Variables	CADF		CIPS		Observations
	At level	Δ	At level	Δ	
CO2	-3.705*** (0.000)	-15.367*** (0.000)	-2.402	-5.476	I(0)
GLOB	-2.753 ** (0.003)	-15.696 *** (0.000)	-2.459	-5.581	I(0)
HDI	0.147 (0.558)	-2.640** (0.004)	-1.456	-3.947	I(1)
ENERGY	-1.547* (0.061)	-13.803*** 0.000	-2.117	-5.223	I(1)

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: Author

4.4 Cointegration test:

The Westerlund bootstrap cointegration test, used to assess long-term cointegration, is shown in Table 8. Table 8 confirms the Westerlund test null hypothesis of no cointegration relationships (robust p-value > 0.05). This outcome rules out the existence of a long-term cointegration relationship between CO2 emissions and the explanatory variables (HDI, GLOB, and ENERGY).

Table 8. Cointegration test results

Westerlund bootstrap test		Value	Robust P-value
Westerlund test	G_T	-1.451	0.100
	G_a	-4.080	0.530
	P_T	-6.754	0.120
	P_a	-2.759	0.180

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: Author

As there is no long-term cointegration, we proceed to estimate the dynamic relationship between CO2 emissions and the independent variables (HDI, GLOB, ENERGY), as well as the lagged dependent variable $CO2_{i,t-1}$, using the DCCE approach.

4.5 Estimation of the Dynamic CCE Model:

Due to slope heterogeneity, CSD in errors, lagged dependent variable, series integration at $I(0)$ and $I(1)$, and lack of long-term cointegration interactions, the DCCE model is the most appropriate approach for estimating the dynamic relationship between "CO₂" and "HDI, GLOB, ENERGY, and $CO_{2,t-1}$ ".

Based on EKC hypothesis, Table 9 provides the empirical findings of the dynamic DCCE model estimating the impact of human development, economic globalization, and renewable energy consumption on carbon dioxide emissions. The analysis concludes that human development significantly and positively affects CO₂ emissions at the 5% significance level ($\beta = 26.47$, $t = 2.66$, $p\text{-value} = 0.008$). Specifically, a 1% increase in HDI is related with a 15.57% to 27.22% rise in CO₂ emissions. This suggests that human development, measured through education, life expectancy, and gross national income per capita, significantly exacerbates environmental degradation.

Moreover, the coefficient "HDI²" the quadratic term of "HDI" is also positive and significant at the 5% level ($\beta = 18.65$, $t = 2.37$, $p\text{-value} = 0.001$), indicating that the impact of HDI on CO₂ emissions continues to increase as human development progresses. These findings align with the conclusions of Lawson (2020) and Balsalobre-Lorente & al. (2018), which highlight those efforts to improve living standards (education, health, and income) lead to greater fossil fuel consumption through increased electricity access, resulting in higher primary energy use and intensifying air pollution.

However, these results contradict the EKC hypothesis in the context of our study. According to the EKC theory, emissions initially rise during the initial phases of economic expansion but eventually decline once a specific development threshold is achieved. At this stage, technological advancements enable the adoption of green technologies, gradually replacing older, polluting technologies and reducing environmental degradation (Soukiazis & al., 2019). These findings are consistent with studies by Amponsah (2023), Beyene (2022), Pata & al. (2021), and Van

Tran & al. (2019), which also rejected the EKC hypothesis in African countries.

Table 9. Estimation results from the DCEE approach

Variables	Dynamic Common Correlated Effects Estimator		
	DCCE MG methode	DCCE Jackknife method	DCCE Recursive method
L.lnCO2	-1.113*** (-12.55)	-1.099*** (-12.36)	-1.074*** (-10.45)
lnHDI	26.47** (2.66)	27.22* (2.37)	15.57 (0.89)
(lnHDI) ²	18.66* (2.37)	17.27* (2.35)	14.23 (1.14)
lnENERGY	-2.123** (-2.63)	-2.366** (-2.76)	-2.332* (-2.51)
lnGLOB	0.00484 (0.05)	0.0139 (0.14)	-0.160 (-0.84)
_cons	5.910 (0.60)	7.556 (0.66)	0.105 (0.32)
<i>N</i>	1050	1050	980
<i>R</i> ²	0.92	0.90	0.74
<i>CD Statistic</i>	0.89	-0.49	-0.22
<i>(p-value)</i>	(0.3708)	(0.6227)	(0.8271)

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: Author

The given coefficient for green energy use aligns with the findings of Soukiazis & al. (2019), Hacıımamoğlu & Cengiz (2024), Adeleye & al. (2023), and Simionescu & al. (2021), which assert that green energy consumption is claimed to contribute to the reduction of atmospheric pollution. Indeed, the results for the ENERGY coefficient ($\beta = -2.123$, $t = -2.63$, $p\text{-value} = 0.009$) indicate that an increase in renewable energy consumption has a significant negative relationship with dioxide emissions at the 5% significance level. Specifically, a one-unit increase in renewable energy use is related with a 2.123% to 2.366% decrease in CO2 emissions.

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Additionally, the coefficient for lagged CO₂ emissions is negatively associated with current emission levels ($\beta = -1.113$, $t = -12.55$, $p\text{-value} = 0.000$). This finding suggests that a reduction in past CO₂ emissions is associated with lower current emissions levels. The negative association potentially reflects a progressive improvement in environmental practices or emission-reduction policies. This result also highlights the significance of historical trends in shaping current emission levels, underlining the impact of measures implemented over time to mitigate environmental degradation.

In contrast, the coefficient for economic globalization shows a slightly positive but statistically insignificant association with carbon emissions. These effects align with the conclusions of Pata & al. (2021) and Simionescu & al. (2021) but differ from those of Adeleye & al. (2023), Huang & al. (2019), and Amponsah (2023), who highlighted that trade liberalization tends to exacerbate CO₂ emissions. The absence of statistical significance suggests that globalization does not have a measurable impact on emission levels, in the context of the countries studied. This could reflect a balance between opposing effects of globalization, such as increased polluting economic activities and the adoption of cleaner technologies facilitated by international openness.

Robustness Check: The Jackknife Bias Correction method and Recursive Mean Adjustment methods were also employed for reducing biases associated with small sample sizes (Jan, 2018). The results obtained from these two techniques are consistent with those produced by the DCCMG (mean group) method, further reinforcing the robustness of the conclusions.

Additionally, the CD statistics indicate weak CSD in the errors. Pesaran's (2015) test was applied, revealing no significant cross-sectional dependence, with a CD statistic of 0.895 and a probability value of 0.371, thus supporting the null assumption of weak dependence.

Furthermore, the R^2 values range from 0.74 to 0.92, indicating an acceptable level of model fit. This suggests that the model's independent

variables (HDI, GLOB, ENERGY) explain 74%–92% of CO₂ emissions variance.

5. CONCLUSION

This research examines the dynamic relationship between human development and carbon dioxide emissions. Specifically, it aims to evaluate the effect of human development, globalization, and renewable energy consumption on atmospheric pollution in African countries from 1990 to 2022, based on Kuznets' hypothesis theory (1955).

The dynamic relationship was estimated using the DCCE estimator, which accounts for country heterogeneity and cross-sectional dependence in the errors while incorporating the lagged dependent variable. The panel data methodology employed proved robust to CSD and slope heterogeneity. To validate the robustness of the results, Pesaran's (2015) test was applied to assess CSD in the estimated model. The findings confirm the robustness of the DCCE estimator, which ensures consistent estimations even in the presence of significant CSD in the baseline model.

The empirical investigation revealed significant interrelationships among the study variables. The results refuted the initial EKC theory, which posits an inverted U-shaped relationship between human development and environmental degradation. Instead, a significant positive link between human development and CO₂ emissions was observed across the 35 African countries analyzed, indicating that environmental degradation intensifies as human development progresses.

Conversely, green energy use and lagged CO₂ emissions demonstrated a negative impact on air pollution in all estimations. In other words, the consumption of green energy mitigates environmental pressure in African countries and contributes to improved environmental quality. These conclusions underscore the importance of adopting green policies to promote sustainable energy sources and reduce emissions over time.

Policy recommendations: Based on the results, some recommendations are proposed for African nations to promote human development while reducing environmental degradation:

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- Align Environmental Priorities with Human Development Strategies: Integrate environmental objectives with strategies focusing on education, healthcare, and reducing inequalities to ensure sustainable and inclusive development.
- Raise Environmental Awareness: Incorporate environmental education into school curricula to foster collective awareness and encourage environmentally friendly behaviors.
- Invest in Green Infrastructure and Low-Carbon Technologies: Redirect revenues from natural resources toward renewable energy production and consumption investments. It would support human well-being while mitigating environmental impacts.

Future research directions: The findings provide valuable insights into the dynamics driving CO₂ emissions. Future research could extend the analysis period to capture long-term dynamics better. Expanding the scope to include a larger sample of developed and developing countries would improve understanding of the determinants of environmental degradation. Additionally, employing long-term estimation methods and classifying countries by income level (high, middle, and low) would offer more nuanced and comparative insights.

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