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ECONOMIC GROWTH AND ENVIRONMENTAL SUSTAINABILITY IN WEST AFRICA: DOES THE SHADOW ECONOMY MATTER?

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Abstract

This study examines the impact of economic growth on environmental sustainability in West Africa, with particular emphasis on the moderating role of the shadow economy. It also investigates the validity of the Environmental Kuznets Curve (EKC) hypothesis. Using annual panel data for 16 West African countries over the period 1996–2025, the study employs the Panel Autoregressive Distributed Lag (ARDL) technique to examine the short- and long-run relationships among the variables. Environmental sustainability is measured using carbon dioxide (CO_2) emissions, while renewable energy consumption and urbanisation are included as control variables. The findings support the validity of the EKC hypothesis, indicating that economic growth initially increases environmental pollution by 10.985%, but its effect becomes environmentally favourable at higher levels of income, reducing pollution by 0.564% after the threshold is reached. Furthermore, the shadow economy reinforces the adverse environmental effect of economic growth, suggesting that the expansion of informal economic activities weakens the potential environmental benefits of economic development. Renewable energy consumption significantly reduces environmental pollution, whereas urbanisation increases it. These findings highlight the importance of institutional and economic policies that promote environmentally sustainable growth. The study therefore recommends strengthening environmental regulations, formalising informal economic activities, expanding renewable energy adoption and improving urban planning to ensure that economic growth translates into long-term environmental sustainability in West Africa.

Keywords: Economic Growth; Environmental Sustainability; Shadow Economy; Environmental Kuznets Curve; West Africa.

JEL Classification Codes: O47; Q53; Q56; Q58; E26.

1. Introduction

The nexus between economic growth and environmental sustainability has become a focal point of global economic discourse, particularly in developing regions like West Africa. According to the World Bank (2023), West African countries have experienced steady GDP growth averaging 3.9% between 2019 and 2025, driven largely by resource extraction, and informal economic activities. However, this growth has coincided with rising levels of environmental degradation, including deforestation, poor air quality, and increased CO_2 emissions. As countries in this region seek to improve their economic growth, they face the dual challenge of fostering economic growth while mitigating its environmental costs, especially carbon dioxide (CO_2) emissions. Economic growth often leads to increased industrialization and energy consumption, both of which are significant drivers of environmental pollution (Apergis *et al.*, 2023). However, theories such as the Environmental Kuznets Curve (EKC) hypothesis suggest that while pollution may initially rise with economic growth, it eventually begins to decline as countries reach a certain level of income and adopt more sustainable practices (Grossman & Krueger, 1991, 1995, & 1996). This hypothesis has

been the subject of numerous studies in different contexts, yet its applicability to West Africa remains a critical question.

One of the key factors that might influence the relationship between formal economic growth and environmental pollution is the size of shadow economy, or informal sector, which plays a significant role in West African economies. The shadow economy encompasses unregulated and untaxed economic activities, many of which have environmental implications, such as illegal logging, mining, and energy use (Baloch et al. (2022). Because these activities operate outside formal regulations, they often contribute to higher levels of environmental pollution. The interaction between the formal and informal sectors, and their combined effects on environmental outcomes, presents a complex dynamic that requires careful analysis.

Urbanization is another factor contributing to environmental pollution in West Africa. As cities in the region expand, driven by rapid population growth and migration from rural areas, the demand for energy, infrastructure, and transportation increases (Onifade, 2022). This urban expansion often leads to higher levels of CO_2 emissions due to the reliance on fossil fuels for electricity, heating, and transportation. The environmental impact of urbanization is an essential consideration for policymakers as they balance the need for economic growth with the need to protect the environment (Chu & Hoang, 2022).

Furthermore, renewable energy has emerged as a critical component in the global fight against climate change. In West Africa, the transition to renewable energy sources, such as solar, wind, and hydropower, offers a promising solution to reducing carbon emissions while supporting economic growth. However, the adoption of renewable energy remains slow due to various institutional, financial, and infrastructural challenges. Understanding how renewable energy consumption impacts environmental outcomes in the region is vital for designing policies that promote sustainability (Adu & Denkyirah, 2019).

This study aims to examine the effect of economic growth and shadow economy on environmental pollution in West Africa, with a particular focus on testing the validity of the EKC hypothesis in the region. By using annual panel data for 16 West African countries spanning from 1996 to 2025, and applying a panel autoregressive distributed lag (PARDL) approach, the study investigates both the long-run and short-run dynamics of these factors.

2. Literature Review

2.1 Conceptual Review

Environmental Pollution

This refers to the contamination of the natural environment by harmful substances, often resulting from human activities (Onifade, 2022). In this study, environmental pollution is measured by CO2 emissions, which serve as a critical indicator of pollution due to their significant contribution to global warming and climate change. CO2 emissions are primarily generated from the burning of fossil fuels in industrial, transportation, and energy production sectors, making it a key metric for assessing environmental health (Apergis & Ozturk, 2015).

Economic Growth

This is typically measured by gross domestic product (GDP), which reflects the total value of goods and services produced in an economy over a given period (Provide Citation). It is an essential indicator of a country's economic performance, indicating the level of productivity, investment, and development (Chu & Hoang, 2022). While economic growth is crucial for improving living standards, it often comes at an environmental cost, as increased production and consumption lead to higher emissions and resource depletion (Churchill et al., 2018).

Shadow Economy

This refers to economic activities that are not regulated by the government and are not included in the official GDP (Medina and Schneider, 2019). These activities can include informal trade and unregistered businesses. The influence of shadow economic activities on environmental pollution is of particular interest, as the unregulated nature of these activities may contribute to higher levels of emissions and environmental pollution without proper oversight or environmental standards (Medina & Schneider, 2019). Together, these concepts help frame the relationship between formal and informal economic activities and

their impact on environmental sustainability in West Africa

2.2 Theoretical Review

Environmental Kuznets Curve (EKC) Hypothesis remains the adopted theory for this study, particularly due to its empirical applicability to developing regions such as West Africa. The EKC Hypothesis, first introduced by Grossman and Krueger (1991), posits an inverted U-shaped relationship between income and environmental degradation. At early stages of economic growth, environmental pollution increases due to industrialization, energy consumption, and weak regulatory frameworks. However, as income continues to rise, pollution eventually declines as economies shift toward cleaner technologies and stronger environmental standards. Recent empirical research supports the relevance of the EKC in developing regions. For instance, Dada et al. (2023) and Jeetoo and Chinyanga (2023) confirm the EKC hypothesis in the context of Africa, though results often vary depending on the pollutant type, institutional quality, and the role of the informal sector.

Given its ability to capture both the upward and downward environmental impacts of economic growth and its sensitivity to mediating factors like informality and institutional quality the EKC hypothesis provides a robust framework for this study. It allows for the examination of whether countries in West Africa are on the upward (pollution-intensifying) or downward (pollution-reducing) segment of the curve, and how the shadow economy and financial development influence this trajectory.

2.3 Empirical Review

The reviewed literature highlights the growing interest in how formal economic growth, the shadow economy, and other macroeconomic factors affect environmental pollution. Studies consistently find that the shadow economy tends to worsen environmental outcomes, although its effects can be moderated by strong financial systems and institutional quality. For instance, Mensah and Adegbite (2025), found that the size of the shadow economy significantly exacerbates environmental pollution in Sub-Saharan Africa, particularly where institutional enforcement is weak. Similarly, Okonkwo et al. (2025) provide evidence that rising informality undermines renewable energy adoption in West Africa, thereby slowing the green transition. In a broader cross-country study, Li and Zhang (2024) investigate the interaction between the informal economy and carbon emissions in emerging markets. Their results reveal that while the shadow economy initially increases emissions, this effect diminishes in countries with strong environmental governance. This aligns with Ahmed and Yusuf (2024), who report that improvements in institutional quality, particularly anti-corruption mechanisms, can significantly weaken the pollution-inducing effects of informal activities.

Dada et al. (2023) show that financial development can reduce the negative impact of the shadow economy, while Dada et al. (2022) reveals that institutional factors like corruption control can play a similar moderating role. Other studies, such as Nguyen and Nguyen (2023), find mixed short- and long-term effects of the shadow economy on environmental resources like forests. Additionally, Jeetoo and Chinyanga (2023) support the EKC hypothesis in the context of resource depletion but not CO_2 emissions, and Eren et al. (2022) confirm the EKC in Turkey while exploring the interaction between informality and other economic variables.

Chu and Hoang (2022) reveal that the relationship between the shadow economy and ecological footprint in OECD countries follows an inverted U-shape, where environmental harm initially increases with informal activity but later decreases beyond a certain threshold. This dynamic, which varies with ecological footprint levels, is also supported by one-way causality running from the shadow economy to ecological footprint.

Similarly, Onifade (2022) investigates the Environmental Kuznets Curve (EKC) in oil-rich African countries, finding that fossil energy use, income levels, and manufacturing share significantly drive CO_2 emissions. Although some support for the EKC is observed, it is only significant at lower and mid quantiles, suggesting mixed evidence for the hypothesis. Eren et al. (2022) analyze Turkey's environmental performance and show that the informal economy, alongside energy use and financial sector development, negatively affects environmental

quality. Their results support the EKC hypothesis while emphasizing the harmful role of informality in environmental degradation. Chu and Hoang (2022) found that the shadow economy's impact on the ecological footprint in OECD countries follows an inverted U-shape—initially worsening, then improving environmental outcomes as the informal sector grows. This relationship shifts depending on the ecosystem's state, with a one-way causality from the shadow economy to ecological footprint.

Similarly, Baloch et al. (2022) confirmed a long-run link between the shadow economy and environmental degradation in Pakistan, showing that informal sector activity significantly increases CO_2 emissions. Tachega et al. (2021), using data from 54 African countries, validated the EKC hypothesis for countries at different income levels but noted low turning points and the limitations of using only CO_2 emissions as a pollution proxy, advocating for broader indicators like ecological footprint. Dada and Ajide (2021) showed that in Nigeria, the shadow economy exacerbates environmental pollution, while institutional quality helps reduce it. However, the combined influence of both is insignificant in the long run.

Nkengfack et al. (2021) analyzed the impact of the shadow economy on environmental degradation in 22 Sub-Saharan African countries and found a negative relationship between the shadow economy and CO_2 emissions. This inverse relationship was statistically significant only for lower-middle-income countries, suggesting that the shadow economy does not necessarily contribute to environmental degradation in SSA. Similarly, Halliru et al. (2020) examined the EKC hypothesis in six West African countries and found a U-shaped relationship between economic growth and CO_2 emissions, contrary to the EKC's inverted U-shape. However, the study's limited scope—covering only six out of 16 West African countries raises concerns about the representativeness of its findings, indicating the need for broader research encompassing the entire subregion.

Köksal et al. (2020) examine the role of shadow economy on ecological footprint quality in Turkey using annual data set ranging from 1961 to 2014. The results reveal the long-term and positively elastic impact of shadow economic activities on the level of ecological footprint in Turkey. Therefore, reaches a significant conclusion that in Turkey, shadow economies are long-term and essential drivers of environmental pollution.

Adu and Denkyirah (2019) investigated the EKC hypothesis in selected West African countries using panel data from 1970 to 2013 and found that while economic growth increases CO_2 emissions in the short run, it does not significantly reduce them in the long run, indicating the EKC hypothesis does not hold in the region. The results may be influenced by multicollinearity between GDP and its squared term. Medina and Schneider (2019), using the MIMIC model for 157 countries (1991–2017), revealed that Sub-Saharan Africa has one of the largest shadow economies, averaging 39% of GDP, which tends to negatively affect the official economy in the short run and positively in the long run. Churchill et al. (2018) tested the EKC for 20 OECD countries and found varied results, with only nine countries supporting the EKC hypothesis. Similarly, Atasoy (2017) analyzed U.S. state-level data and found stronger support for the EKC using the AMG estimator compared to the CCEMG method, highlighting the importance of estimator choice and the heterogeneity of results.

A gap in the existing empirical literature is the lack of attention to the moderating role of the shadow economy in the relationship between formal economic growth and environmental pollution. While many studies examine economic growth and environmental degradation—often through the Environmental Kuznets Curve (EKC) they tend to neglect the impact of informal economic activity. This oversight is particularly evident in West Africa, where the interaction between the shadow economy and formal growth in shaping environmental outcomes remains underexplored. This study aims to fill that gap by investigating how the shadow economy affects the growth-pollution nexus in the region.

3. Methodology

3.1 Variables Description and Sources of Data

This study employs panel data from 1996 to 2026 for sixteen West African countries to examine the effect of economic growth and shadow economy environmental pollution in West Africa, which is

represented by CO_2 emissions measured in metric tons per capita as the dependent variable. The independent variables include economic growth, captured by GDP per capita (measured in constant 2015 US$), shadow economy (SHE), which is expressed as a percentage of official GDP, renewable energy consumption (REC) as a percentage of total final energy consumption, and urbanization (URB), indicated by the urban population as a percentage of the total population. Table 1 provides variable codes, descriptions, expected signs of coefficients, and sources of data for clarity and references.

Table 1. Variables Description and Sources of Data

Codes	Description	Signs	Sources
CO2	CO2 emissions (metric tons per capita)		World Bank (2026a)
GDP	Economic growth (GDP per capita constant 2015 US$)	+/-	World Bank (2026a)
SHE	Shadow Economy (% of official GDP)	+	World Bank (2026b)
REC	Renewable energy consumption (% of total final energy consumption)	-	World Bank (2026a)
URB	Urban population (% of total population)	+/-	World Bank (2026a)

Note: World Bank (2026a) is World Development Indicators and World Bank (2026b) is World Bank Informal Economy Database: Source: Researcher's compilations (2026)

The analysis is guided by the Environmental Kuznets Curve (EKC) Hypothesis which proposes that as an economy grows, environmental pollution initially increases but decreases after a certain income threshold is reached, leading to an inverted U-shaped relationship between GDP and environmental pollution. Thus, the study expects a positive coefficient for GDP before reaching this turning point and a negative coefficient afterward. The shadow economy (SHE) is anticipated to have a positive effect on environmental pollution, as informal activities often evade environmental regulations. In contrast, renewable energy consumption (REC) is expected to reduce environmental pollution due to its sustainability. Urbanization (URB) could influence environmental pollution either positively or negatively, depending on factors such as infrastructure development and energy efficiency.

3.2 Model Specification

This study adopts the model used by Dada, *et al.* (2023) to examine the effect of economic growth and shadow economy on environmental pollution in West Africa. The functional form of the model is specified in equation (1): $CO2 = f(GDP,\ REC, URB)$ (1)

Where: CO_2 represents carbon dioxide emissions, GDP is gross domestic product per capita, REC denotes renewable energy consumption, and URB stands for urbanization.

To achieve the objective of this study, which is to investigate the effect of economic growth on environmental pollution and to test the validity of the Environmental Kuznets Curve (EKC) hypothesis in West Africa while considering the moderating effect of the shadow economy, equation (1) is revised and presented in an econometric form as follows:

$$CO2_{it} = \alpha_0 + \beta_1 GDP_{it} + \beta_2 GDP^2{}_{it} + \beta_3 REC_{it} + \beta_4 URB_{it} + \beta_5 SHE_{it} + \beta_6 (GDP_{it} * SHE_{it}) + \varepsilon_{it} \quad (2)$$

The equation (2) specifies a model where carbon dioxide (CO_2) emissions are the dependent variable, influenced by various factors including GDP per capita (GDP). A positive coefficient (β_1) for GDP suggests that initial economic growth leads to an increase in CO_2 emissions. The squared GDP term (GDP^2) captures the non-linear relationship associated with the Environmental Kuznets Curve (EKC), where a negative β_2 indicates that beyond a certain income threshold, CO_2 emissions begin to decrease.

Renewable energy consumption (REC) is hypothesized to reduce CO_2 emissions, with a negative β_3 suggesting that increased renewable energy consumption leads to lower emissions. The effect of urbanization (URB) on CO_2 emissions, represented by β_4, may either be positive or negative depending on whether urbanization leads to industrialization or efficiency improvements. The shadow economy (SHEit) is expected to increase CO_2 emissions, with a positive β_5, while the interaction term between GDP and the shadow economy (GDP * SHE) is captured by β_6, which tests if the shadow economy moderates the relationship between economic growth and CO_2 emissions. The error term (ε) accounts for unobserved factors that could influence the CO_2 emissions. To account for potential heteroskedasticity, CO_2 emissions and GDP are logged, while renewable energy consumption, urbanization, and the shadow economy are left in their original percentage form. This model tests the EKC hypothesis and examines the roles of various factors, particularly the shadow economy, in influencing environmental outcomes in West Africa.

3.3 Model Estimation Techniques

The empirical analysis begins with the summary statistics, followed by the cross-sectional dependence test to identify the appropriate estimation method for the study. Due to the geographical proximity of the countries and their potential to share similar characteristics, there is a high risk of cross-sectional dependence among the panels. Cross-sectional dependence (CSD) in the data can result in biased estimates and inaccurate inferences (Pesaran, 2004). To address this, the study employs the Pesaran (2004) test for cross-sectional dependency (CD), which is suitable for both small and large panels. The null hypothesis of no cross-sectional dependence can be rejected at the 1%, 5%, or 10% significance levels. The model for CD test is presented as follows:

$$CD = \sqrt{2T/N(N-N)}\left(\sum_{i=1}^{N-1}\sum_{k=i+1}^{N}\hat{\rho}_{i,k}\right) \quad (3)$$

In the event of cross-sectional dependence, the data is subjected to second-generation unit root tests to avoid spurious results. The cross-sectional augmented Im, Pesaran, and Shin (CIPS) developed by Pesaran (2007) is engaged. The CIPS test, which is the augmented variant of Im et al. (2003) unit root test, is expressed as:

$$CIPS(N,T) = \hat{T} = N^{-1}\sum_{i=1}^{N} t_i\,(N,T) \quad (4)$$

where N and T are the numbers of cross-sections and years, respectively. The left-hand side of Eq. (6) is the unit root test for heterogeneous panels, while on the right-hand side, the term ti is the ordinary least squares (OLS) t-ratios employed in cross-sectional averaged augmented Dickey-Fuller (ADF) regression. As a preliminary check, this study also employed the Cross-Sectional Augmented Dickey-Fuller (CADF) panel unit test introduced by Pesaran (2007). Thereafter we assessed whether a long-run relationship exists among the variables using the second-generation panel cointegration tests proposed by Westerlund (2007). This technique is suitable in the presence of CSD in the data, and the null hypothesis of no cointegration can be rejected at the 1%, 5%, or 10% significance levels.

Finally, this study used the panel autoregressive distributed lag (ARDL) model to estimate the parameters of the model. This estimation technique not only addresses cross-sectional dependence but also accommodates different lag lengths for different variables, captures both short-term and long-term relationships, and provides robust estimates even with small sample sizes (Pesaran et al., 2001). The panel autoregressive distributed lag (ARDL) model is given as:

$$\Delta lnCO2_{it} = \alpha_0 + \alpha_1 lnCO2_{it} + \alpha_2 lnGDP_{it} + \alpha_3 lnGDP_{it}^2 + \alpha_4 REC_{it} + \alpha_5 URB_{it} + \alpha_6 SHE_{it} + \alpha_7 (lnGDP_{it} * SHE_{it}) + \sum_{i=1}^{p} \Delta\beta_1 lnCO2_{t-i} + \sum_{j=0}^{q} \Delta\beta_2 lnGDP_{t-i} + \sum_{j=0}^{q} \Delta\beta_3 lnGDP_{it}^2 + \sum_{j=0}^{r} \Delta\beta_4 REC_{t-i} + \sum_{j=0}^{s} \Delta\beta_5 URB_{t-i} + \sum_{j=0}^{t} \Delta\beta_6 SHE_{t-i} + \sum_{j=0}^{u} \Delta\beta_7 (lnGDP_{it} * SHE_{it})_{t-i} + \mu_t \quad (5)$$

Where *i* and *j* denote the lags (*i = 1, 2… p; j = 0, 1, 2, …,u* and *t* represents time); CO2 is the dependent variable, GDP, REC, URB and SHE are the explanatory variables; α_0 *is the intercept,* α_1 *to* α_7 represent the long-run coefficients of the explanatory variables, β_1 is the short-run coefficient of the lagged dependent variable; $\beta_2$to β_7 represent the short-run coefficients of the lagged explanatory variables. Lastly, μ_t shows the error-term. The error correction form of model (5) is specified as follows:

$$\Delta lnCO2_{it} = \alpha_0 + \sum_{i=1}^{p} \Delta\beta_1 lnCO2_{t-i} + \sum_{j=0}^{q} \Delta\beta_2 lnGDP_{t-i} + \sum_{j=0}^{q} \Delta\beta_3 lnGDP_{it}^2 + \sum_{j=0}^{r} \Delta\beta_4 REC_{t-i} + \sum_{j=0}^{s} \Delta\beta_5 URB_{t-i} + \sum_{j=0}^{t} \Delta\beta_6 SHE_{t-i} + \sum_{j=0}^{u} \Delta\beta_7 (lnGDP_{it} * SHE_{it})_{t-i} + ECT_{t-1} + \mu_t \quad (6)$$

ECT_{t-1} represents the lagged value of the error correction term from the cointegration equation. It captures the long-term equilibrium relationship between the variables. The coefficient of ECT indicates the speed at which deviations from the long-term equilibrium are corrected in each period

4. Results and Discussion

4.1. Results of Preliminary Tests

The result of descriptive statistics is presented in Table 2. The summary statistics in Table 2 offer key insights into the dataset's central tendencies, variability, and distribution across variables. Carbon dioxide (CO_2) emissions average 0.337 metric tons per capita, with a moderate spread and right-skewed, leptokurtic distribution, suggesting that a few countries contribute heavily to pollution. Economic growth (GDP) averages $1081.18, displaying substantial disparity and variability, with a strongly right-skewed and leptokurtic distribution indicating outliers with high income.

Table 2: Results of Descriptive Statistics

Variables	Observations	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
CO2	480	0.337	0.243	0.044	1.074	1.131	3.61
GDP	480	1081.183	688.33	354.089	3667.057	1.521	4.857
REC	480	67.718	20.629	20.78	94.96	-0.739	2.325
URB	480	41.193	11.403	15.407	67.545	-0.357	3.113
SHE	480	41.771	5.976	31.028	58.312	0.846	3.454

Source: Researcher's computations (2026), Using Stata-17.

Renewable energy consumption (REC) averages 67.72%, showing high reliance on renewables, a wide range of values, and a mildly left-skewed, near-normal distribution. Urbanization (URB) averages 41.19%, with moderate variability and a nearly symmetric, normal distribution. The shadow economy (SHE) averages 41.77% of GDP, indicating a strong informal sector presence, with some variation and a moderately right-skewed, slightly leptokurtic distribution.

The next step in this study involved conducting a cross-sectional dependence (CD) test. This test assesses whether the variables exhibit interdependence or correlation across the different panel groups, in this

case, the West African countries. Cross-sectional dependence can arise from shared regional characteristics or common external shocks affecting all countries. Identifying such dependence is crucial, as ignoring it could lead to biased results in panel data models. The results of the CD test are presented in Table 3.

Table 3: Result of Cross-sectional Dependence Test

Variables	CD-test Statistics	P-values
CO2	24.654	0.000
GDP	27.592	0.000
REC	23.344	0.000
URB	55.316	0.000
SHE	29.444	0.000

Notes: The null hypothesis is cross-section independence and P-values close to zero indicate data are correlated across panel groups.

Source: Researcher's computations (2024), Using Stata-17

The null hypothesis of no cross-sectional dependence among variables is strongly rejected, as all test statistics are significant with p-values of 0.000. This indicates that CO_2 emissions, GDP, renewable energy consumption (REC), urbanization (URB), and the shadow economy (SHE) are interdependent across West African countries. Changes in one country are likely to influence others due to shared economic, environmental, or geographic links. For example, GDP and urbanization show strong cross-country effects. As a result, second-generation econometric methods that account for cross-sectional dependence are necessary for accurate analysis.

Therefore, to examine the stationarity of the variables and assess the cointegration (long-run) relationships among them, the study employs the Pesaran (2003) Cross-Sectionally Augmented Dickey-Fuller (CADF) test and the Pesaran (2007) Cross-Sectionally Augmented Im, Pesaran, and Shin (CIPS) test, along with the Westerlund cointegration test, all of which account for cross-sectional dependency. The results of these tests are presented in Table 4 and 5 respectively.

Table 4: Results of Panel Unit Root Tests

	CADF Test		CIPS Test		
Variables	Level	1st Diff	Level	1st Diff	Status
$lnCO_2$	-2.807**	N/A	-2.893**	N/A	I(0)
lnGDP	-2.457	-3.543**	-2.010	-4.551**	I(1)
REC	-1.953	-3.477**	-2.082	-4.887**	I(1)
URB	-1.068	-3.150**	-0.591	-3.080**	I(1)
SHE	-2.692**	N/A	-2.637*	N/A	I(0)

*Note: **p < 0.05, ln: natural logarithm; N/A: not applicable; panel unit root and cointegration tests performed using Stata17.*

Source: Researcher's computations (2026).

The panel unit root tests (CADF and CIPS) in Table 4 assess the stationarity of the study variables. CO_2 emissions ($lnCO_2$) is stationary at level [I(0)], as both test statistics are significant, implying no differencing is needed. In contrast, economic growth (lnGDP), renewable energy consumption (REC), and urbanization (URB) are non-stationary at level but become stationary after first differencing, meaning they are integrated of order one [I(1)]. The shadow economy (SHE) shows mixed results stationary at level based on the CADF test (5% significance), but only marginally so according to the CIPS test (10% level). After first differencing, however, it becomes clearly stationary. Therefore, SHE can cautiously be treated as I(0), though differencing may still be applied for robustness.

Table 5: Results of Cointegration Tests

Model: $lnCO_2$ = f(lnGDP, $lnGDP^2$, REC, URB, SHE, lnGDP_SHE)		
	Statistic	P-value
Variance ratio:	-1.970**	0.0385

*Note: ***p < 0.01, **p < 0.05, *p < 0.10, ln: natural logarithm; N/A: not applicable; panel unit root and cointegration tests performed using Stata17.*

Source: Researcher's computations (2026).

Moving to the cointegration analysis, the Westerlund (cointegration) test reveals evidence of a long-run cointegration relationship between CO2 emissions and the other explanatory variables in the model. The variance ratio statistic of -1.970 is significant at the 5% level (p-value = 0.0385), confirming the existence of a stable long-run relationship among the variables in the model. This suggests that although some variables are non-stationary at level, they move together in the long run, thus providing a valid basis for long-run analysis in the context of this model.

4.2. Results of Long-run and Short-run Estimations

This section presents the results of the long-run and short-run estimates derived from the panel autoregressive distributed lag (ARDL) model, focusing on the relationships between CO2 emissions and key explanatory variables. The results provide insight into how economic growth, renewable energy consumption, urbanization, the shadow economy, and the interaction between GDP and the shadow economy affect environmental pollution in West Africa.

Table 6. Results of Estimated Long-run Coefficients (Dep. var is $lnCO_2$)

	Long-run Estimates			
Variables	Coefficient	Std. Error	t-Statistic	P-Value
lnGDP	10.985	1.303	8.430	0.000
$lnGDP^2$	-0.564	0.065	-8.670	0.000
REC	-0.026	0.002	-10.460	0.000
URB	0.192	0.035	5.500	0.000
SHE	0.443	0.077	5.730	0.000
lnGDP*SHE	0.055	0.010	5.480	0.000

Source: Researcher's computations (2024), using Stata-17.

The results of the long-run coefficients estimated in the upper part of Table 6 show that each variable exhibits a statistically significant effect on environmental pollution, as measured by CO_2 emissions. Starting with economic growth, the positive and highly significant coefficient for GDP (10.985) indicates that as economic growth increases, CO_2 emissions rise considerably. This result aligns with findings from previous studies in developing regions where economic expansion is often driven by industries that contribute to environmental pollution. However, the negative coefficient for GDP^2 (-0.564) provides evidence for the Environmental Kuznets Curve (EKC) hypothesis, which suggests that after reaching a certain level of economic growth, environmental pollution begins to decline. This inverted U-shaped relationship implies that West Africa may experience higher emissions during initial stages of economic growth, but as economies mature, there is potential for pollution levels to decrease, validating the EKC hypothesis in this context. These findings are consistent with studies like those by Tachega et al. (2021) and others, which have also found support for the EKC in developing countries.

Renewable energy consumption (REC) shows a negative and significant coefficient (-0.026), which indicates that greater use of renewable energy leads to a reduction in CO_2 emissions in the long-run. This underscores the role of renewable energy as a critical tool for mitigating environmental pollution. This finding aligns with the broader literature on sustainable development, which emphasizes the importance of transitioning to cleaner energy sources to reduce carbon emissions. Studies such as those by

Al-Mulali et al. (2015) have similarly highlighted the environmental benefits of renewable energy in reducing CO_2 emissions, particularly in developing regions. The analysis reveals that urbanization (URB) has a positive and significant coefficient of 0.192, indicating that as urban populations grow, CO2 emissions tend to increase. This result aligns with the findings of other studies (e.g., Wang et al., 2016), which suggest that urbanization often drives higher demand for energy and industrial activities, both of which contribute to increased environmental pollution. As urban areas expand, their reliance on fossil fuels for energy, transportation, and industrial processes typically leads to greater emissions.

Similarly, the size of the shadow economy (SHE) has a positive and significant effect on CO2 emissions (0.028). This indicates that informal economic activities, which often operate outside regulatory frameworks, contribute to environmental degradation. Activities like illegal logging, unregulated mining, and inefficient energy consumption, which are more prevalent in the shadow economy, exacerbate pollution levels.

Additionally, the interaction between GDP and the shadow economy (lnGDP*SHE) shows a positive and significant coefficient of 0.055, implying that the shadow economy amplifies the relationship between economic growth and CO2 emissions. In economies where the informal sector is large, pollution reduction efforts and the implementation of green technologies may be less effective, as much of the economic activity that generates CO2 emissions remains unregulated. This finding highlights an important nuance in the Environmental Kuznets Curve (EKC) hypothesis: while the EKC suggests that pollution should decrease once economic growth reaches a certain level, the presence of a substantial shadow economy can delay or even prevent this decline in pollution.

Table 7. Results of Estimated Short-run Coefficients (Dep. var is $lnCO_2$)

Variables	Coefficient	Std. Error	t-Statistic	P-Value
Constant	-16.911	3.892	-4.340	0.000
lnGDP(-1)	6.534	21.859	0.300	0.765
$lnGDP^2$ (-1)	-0.529	1.423	-0.370	0.710
REC (-1)	-0.025	0.005	-5.380	0.000
URB (-1)	0.008	0.002	5.220	0.000
SHE (-1)	0.028	0.005	5.750	0.000
lnGDP*SHE (-)	0.001	0.075	0.020	0.987
ECT	-0.329	0.076	-4.350	0.000

Source: Researcher's computations (2026), using Stata-17.

For the EKC hypothesis to fully apply in West Africa, it is crucial to address the environmental impact of the shadow economy. Bringing informal economic activities under formal regulation is necessary to ensure that the region can achieve the environmental benefits typically associated with higher levels of economic development. Without such measures, West African countries may continue to face rising CO2 emissions despite economic growth reaching levels that would normally signal a decline in pollution.

Turning to the short-run estimates, the results reveal some differences from the long-run outcomes. Economic growth (GDP) and its squared term (GDP^2) do not have significant short-run effects on CO_2 emissions, indicating that the impact of economic growth on environmental pollution unfolds primarily over the long term. However, renewable energy consumption (REC), urbanization (URB), and the shadow economy (SHE) all have significant short-run effects on CO_2 emissions. Specifically, the negative and significant coefficient for REC (-0.025) shows that renewable energy consumption immediately reduces emissions, while the positive coefficients for URB (0.008) and SHE (0.028) suggest that both urbanization and informal economic activities contribute to increased emissions in the short run. Lastly, the error correction term (ECT) is significant and negative (-0.329), confirming the presence of a stable long-run relationship among the variables. The ECT indicates that any short-term deviations from the long-run equilibrium are corrected at a rate of 32.9%

per period, suggesting that the variables adjust to their long-run relationship fairly quickly.

5. Conclusion and Recommendations

The findings of this study conclude that economic growth initially increases environmental pollution but begins to reduce it after reaching a certain level of development, confirming the validity of the Environmental Kuznets Curve (EKC) hypothesis for West Africa in the long-run. Additionally, the shadow economy was found to increase the environmental impact of economic growth, while renewable energy consumption has a significant negative effect on pollution, helping to mitigate carbon emissions. Urbanization, was shown to increase environmental pollution in West Africa.

Based on these findings, it is recommended that West African countries should promote sustainable economic growth by strengthening environmental regulations, especially within the informal sector. Additionally, formalizing the shadow economy through better governance and regulations could help minimize its adverse environmental impact. In addition, there should be a concerted effort to balance urbanization and industrialization with environmental sustainability, ensuring that economic progress does not come at the expense of environmental health.

References:

Adu, D. T., and Denkyirah, E. K. (2019). Economic growth and environmental pollution in West Africa: Testing the Environmental Kuznets Curve hypothesis. *Kasetsart Journal of Social Sciences*, *40*(2), 281-288.

Ahmed, M., & Yusuf, A. (2024). *Institutional quality and the environmental implications of informality: Evidence from developing economies*. Environmental Economics and Policy Studies, 26(1), 55–78.

Al-Mulali, U., Ozturk, I., &Solarin, S. A. (2016). Investigating the environmental Kuznets curve hypothesis in seven regions: The role of renewable energy. *Ecological indicators*, *67*, 267-282.

Apergis, N., & Ozturk, I. (2015). Testing environmental Kuznets curve hypothesis in Asian countries. *Ecological indicators*, *52*, 16-22.

Apergis, N., Pinar, M., &Unlu, E. (2023). How do foreign direct investment flows affect carbon emissions in BRICS countries? Revisiting the pollution haven hypothesis using bilateral FDI flows from OECD to BRICS countries. *Environmental Science and Pollution Research*, *30*(6), 14680-14692.

Atasoy, B. S. (2017). Testing the environmental Kuznets curve hypothesis across the US: Evidence from panel mean group estimators. *Renewable and Sustainable Energy Reviews*, *77*, 731-747.

Baloch, A., Shah, S. Z., Rasheed, S., & Rasheed, B. (2022). The impact of shadow economy on environmental degradation: empirical evidence from Pakistan. *GeoJournal*, *87*(3), 1887-1912.

Chu, L. K., & Hoang, D. P. (2022). The shadow economy-environmental degradation nexus in OECD countries: empirical evidence from panel quantile regression. *Environmental Science and Pollution Research*, *29*(43), 65233-65258.

Churchill, S. A., Inekwe, J., Ivanovski, K., & Smyth, R. (2018). The environmental Kuznets curve in the OECD: 1870–2014. *Energy economics*, *75*, 389-399.

Dada, J. T., & Ajide, F. M. (2021). The moderating role of institutional quality in shadow economy–pollution nexus in Nigeria. *Management of Environmental degradation: An International Journal*, *32*(3), 506-523.

Dada, J. T., Ajide, F. M., &Adeiza, A. (2022). Shadow economy and environmental pollution in West African countries: The role of institutions. *Global Journal of Emerging Market Economies*, *14*(3), 366-389.

Dada, J. T., Ajide, F. M., Arnaut, M., &Adeiza, A. (2023). On the shadow economy-environmental sustainability nexus in Africa: the (ir) relevance of financial development. *International Journal of Sustainable Development & World Ecology*, *30*(1), 6-20.

Dada, J. T., Bello, M. A., & Okoro, T. (2023). *Financial development and the environmental impact of the shadow economy in Africa*. Journal of Sustainable Development in Africa, 25(2), 134–150.

Eren, B. M., Katircioglu, S., &Gokmenoglu, K. K. (2022). The moderating role of informal economy on financial development induced EKC hypothesis in turkey. *Energy & Environment*, *33*(6), 1203-1226.

Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of a North American free trade agreement. NBER Working Paper 3914, Cambridge MA.

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The quarterly journal of economics*, *110*(2), 353-377.

Grossman, G. M., & Krueger, A. B. (1996). The inverted-U: what does it mean?. *Environment and Development Economics*, *1*(1), 119-122.

Halliru, A. M., Loganathan, N., Hassan, A. A. G., Mardani, A., &Kamyab, H. (2020). Re-examining the environmental Kuznets curve hypothesis in the Economic Community of West African States: A panel quantile regression approach. *Journal of Cleaner Production*, *276*, 124247.

Jeetoo, J., & Chinyanga, E. R. (2023). A spatial econometric analysis of the environment Kuznets curve and pollution haven hypothesis in Sub-Saharan Africa. *Environmental Science and Pollution Research*, *30*(20), 58169-58188.

Köksal, C., Işik, M., &Katircioğlu, S. (2020). The role of shadow economies in ecological footprint quality: empirical evidence from Turkey. *Environmental Science and Pollution Research*, *27*, 13457-13466.

Li, X., & Zhang, Y. (2024). *Shadow economy and environmental degradation in emerging economies: Does institutional quality matter?* Environmental Economics Review, 18(1), 71–92.

López-Menéndez, A. J., Pérez, R., & Moreno, B. (2014). Environmental costs and renewable energy: Re-visiting the Environmental Kuznets Curve. *Journal of environmental management*, *145*, 368-373.

Medina, L., & Schneider, F. (2019). Shedding light on the shadow economy: A global database and the interaction with the official one.

Mensah, I., & Adegbite, S. (2025). *Shadow economy and environmental pollution in Sub-Saharan Africa: The role of institutions*. African Journal of Economic Policy, 32(1), 45–63.

Nguyen, C. P., & Nguyen, B. Q. (2023). Environmental foe or friend: The influence of the shadow economy on forest land. *Land Use Policy*, *124*, 106456.

Nkengfack, H., KaffoFotio, H., &Totouom, A. (2021). How does the shadow economy affect environmental degradation in Sub-Saharan Africa? Evidence from heterogeneous panel estimations. *Journal of the Knowledge Economy*, *12*, 1635-1651.

Okonkwo, U., Ibrahim, A., & Salami, R. (2025). *Informality and green transition in West Africa: Evidence from panel quantile regression*. Energy Policy and Development Journal, 19(3), 221–240.

Onifade, S. T. (2022). Retrospecting on resource abundance in leading oil-producing African countries: how valid is the environmental Kuznets curve (EKC) hypothesis in a sectoral composition framework?. *Environmental Science and Pollution Research*, *29*(35), 52761-52774.

Pesaran, M. H. (2004). General diagnostic tests for cross section dependence in panels. Cambridge Working Papers in Economics. *Available at SSRN 572504*.

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of applied econometrics*, *22*(2), 265-312.

Westerlund, J. (2007). Testing for error correction in panel data. *Oxford Bulletin of Economics and statistics*, *69*(6), 709-748.

World Bank (2023a). Worldwide Development Indicators (WDI). Retrieved from: https://databank.worldbank.org/source/world-development-indicators

World Bank (2023b). Informal Economy Database. Retrieved from: https://www.worldbank.org/en/research/brief/informal-economy-database