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IMPACT OF CARBON MARKET PERFORMANCE ON ENVIRONMENTAL SUSTAINABILITY IN SUB-SAHARAN AFRICA: THE INTERACTIVE ROLE OF REGULATORY QUALITY

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ABSTRACT

This study examines the long-run and short-run effects of carbon market development on environmental degradation in Sub-Saharan Africa, with the interactive role of regulatory quality. The study employed annual panel data for selected 13 Sub-Saharan African countries and utilized the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) estimator to account for cross-sectional dependence, slope heterogeneity, and mixed orders of integration among the variables. Carbon dioxide (CO_2) emissions per capita served as the proxy for environmental degradation, while carbon market development, renewable energy transition, regulatory quality, and the interaction between carbon market and regulatory quality constituted the explanatory variables. The long-run estimates indicate that carbon market development exerts a negative and statistically significant effect on CO_2 emissions. Similarly, energy transition significantly reduces carbon emissions, highlighting its importance in achieving environmental sustainability. However, regulatory quality and its interaction with the carbon market were found to exert statistically insignificant long-run effects, suggesting that the current institutional framework in many Sub-Saharan African countries has not been sufficiently effective in strengthening the environmental benefits of carbon market mechanisms. The study concludes that carbon market development and renewable energy transition are effective policy instruments for reducing carbon emissions in Sub-Saharan Africa, whereas institutional quality and the interaction term are found to be insignificant in affecting CO_2 emission in SSA region. Having established the long-run relationship among the variables the study the SSA government should invest in establishing and expanding carbon trading schemes, incentivizing businesses to adopt low-carbon technologies and comply with emission reduction targets while promoting renewable energy adoption. second, governments should prioritize renewable energy investments through increased public expenditure, tax incentives, subsidies, and improved access to climate finance. Finally, governments should strengthen environmental governance by improving regulatory enforcement and increasing institutional transparency. That is, effective implementation of environmental policies is more important than merely adopting new regulations in SSA region.

Keywords: Environmental degradation, CO_2 emissions, Carbon market, Renewable energy transition, Regulatory quality, CS-ARDL, Sub-Saharan Africa.

JEL Classification: *E31, I32, H53*

1.1 Introduction

Environmental sustainability is the key to human development as it plays an important role in affecting the well-being, life expectancy and ecological stability. It provides essential services such as clean air, water, and fertile soil, which are fundamental for human survival and economic prosperity. However, growing economic activities such as industrialization, urbanization, and population growth have placed significant pressure on natural ecosystems, thereby intensifying environmental challenges, particularly in developing regions such as Africa (Barra et al., 2025; Karimi et al., 2023; Sachs et al., 2019).

United Nations Framework Convention on Climate Change (UNFCCC, 2024) reported that Africa occupies a strategic position in the global environmental sustainability discourse because of its rich natural resource endowment and ecological diversity. The continent hosts vast forest reserves, diverse wildlife, fertile agricultural lands, and extensive mineral resources. According to the Food and Agriculture Organization (FAO), forests cover approximately 22 percent of Africa's total land area and play an essential role in carbon sequestration, biodiversity conservation, and climate regulation (FAO, 2020). These forest ecosystems serve as important carbon sinks that help mitigate global climate change by absorbing carbon dioxide emissions from the atmosphere. The carbon sink capacity varies across Africa because of differences in forest coverage, ecosystem and land-use. For example, the West Africa and Ease African regions account between 10 to 15 percent of global land carbon sink which is very low when compared to Central Africa due to its Congo Basin forest, which cover more than 200 hectares. However, increasing anthropogenic activities such as agricultural expansion, logging, mining, and infrastructure development have exerted significant pressure on these natural ecosystems, leading to increased environmental degradation across many African countries (UNFCCC, 2024).

Despite its abundant natural resources, Africa contributes relatively little to global greenhouse gas emissions but remains highly vulnerable to the adverse impacts of climate change. Intergovernmental Panel on Climate Change indicate that Africa accounts for roughly 3 percent of global carbon dioxide emissions, which is considerably lower than emissions from developed regions such as North America, Europe, and Asia (IPCC, 2022). On a per-capita basis, carbon emissions in Africa average about 0.8 metric tons per person annually, compared with a global average exceeding 4 metric tons (World Bank, 2023). Nevertheless, African countries particularly SSA region face disproportionate environmental consequences, including increasing desertification, water scarcity, and declining agricultural productivity, largely due to their high dependence on climate-sensitive sectors such as agriculture and forestry (UNEP, 2021).

In recent years, market-based environmental policy instruments have gained significant attention as effective mechanisms for addressing environmental degradation and climate change. Among these instruments, the carbon market has emerged as one of the most important tools for promoting environmental sustainability by reducing greenhouse gas emissions and encouraging cleaner production practices. According to American Carbon Registry (ACR, 2024), carbon market refers to a system in which carbon emission permits or carbon credits are traded among firms, industries, or countries, thereby creating economic incentives for reducing carbon emissions. The central idea behind carbon markets is that placing a price on carbon emissions encourages polluters to reduce emissions in the most cost-effective manner (ACR, 2024: Nordhaus, 2019).

The performance of carbon market in SSA has improved gradually over the years, as the region currently host more than 100 carbon credit projects across over 20 African nations, generating approximately 90 million ton of CO_2 equivalent emission reduction annually. This indicates that carbon trading is becoming an important mechanism for financing climate mitigation projects across SSA (Africa Carbon Market Size & Share Report, 2023: Gold Standard, 2024). Furthermore, carbon market initiatives have begun to expand across several African countries as governments seek innovative approaches to financing climate mitigation efforts. For instance, countries such as Nigeria, Kenya, South Africa, and Ghana have initiated policies aimed at developing carbon trading frameworks and attracting investments in carbon credit projects. For example, in the year 2020, Africa issued about 30-35 million tons of carbon credits through voluntary carbon projects, before rising around 40-45 million tons with Africa experiencing 36% market growth in 2021. The credit issuance rose further to roughly 54 million tons of carbon credits, representing over $104 billion global carbon pricing revenue in 2023 (WB, 2024). Finance in Africa (2026) reported that in 2024, SSA countries issued around 24% of global voluntary carbon credits, mainly from cookstove, forestry, and land-use projects These initiatives provide financial incentives for firms and communities to engage in environmentally sustainable practices such as afforestation, renewable energy generation, and climate-smart agriculture. By encouraging the adoption of low-carbon technologies and sustainable land-use practices, carbon markets can significantly contribute to environmental sustainability in African economies (Yang & Tol, 2025).

Given the increasing environmental challenges facing African countries, improving regulatory quality has become an essential component of sustainable environmental management. Strengthening regulatory institutions can enhance the effectiveness of carbon market initiatives, reduce the environmental impacts of the shadow economy, and promote compliance with environmental standards. By improving the design and enforcement of environmental regulations, governments can create an enabling environment for sustainable economic development while protecting natural ecosystems. Empirical studies opined that regulatory quality is relatively weak in SSA region when compared to other regions of the world, although gradual improvements have been observed over the past decade (Damania et al., 2004). Despite this improvement, the region still experiencing poor governance and weak regulatory framework especially in environmental sector (Umar & Abdullahi, 2025). Generally, World Governance Indicator (WGI) in 2025 reported that the values for regulatory framework rages between -1.0 and -0.3 indicating many countries facing institutional weakness in SSA region (WGI, 2025). Therefore, poor regulatory framework may constraints the development of carbon markets by increasing uncertainty, reducing investors' confidence and weakening institutional credibility. Therefore, examining the relationship between carbon markets and environmental sustainability in SSA countries remains an important area of empirical research, particularly in understanding how market-based environmental policies can contribute to sustainable development across the continent. Hence. This study examined the impact of carbon market performance on environmental sustainability in SSA with the role of institutional quality. The study covers thirteen countries namely; Congo DR, Eritrea, Ethiopia, Ghana, Kenya, Mali, Malawi, Madagascar, Nigeria, South-Africa, Tanzania, Uganda and Zambia. The selection of these countries is based on the availability of data especially on carbon credits issuance.

2.1 Empirical Literature on Carbon Market and Environmental Degradation

Yang and Tol (2025) investigated the interaction between multiple environmental markets including carbon trading using panel data for Chinese firms from 2000 to 2024. The study applied a difference-in-difference and artificial counterfactual approach to assess the policy effects. The findings revealed that carbon trading schemes can reduce pollution and influence corporate environmental performance. In the same vein, Biancalani et al. (2024) empirically examined the impact of the European Union Emissions Trading System (EU-ETS) on carbon dioxide emissions in Europe. The study employed a matrix completion method with fixed effects to construct a counterfactual scenario of emissions in the absence of the carbon market. Using panel data covering EU countries from 2005 to 2020, the results showed that the EU carbon market significantly reduced CO_2 emissions in regulated industries. Specifically, emissions significantly declined when compared with the estimated counterfactual scenario, suggesting that carbon markets can be an effective instrument for mitigating environmental pollution. Zhang et al. (2024) investigated the causal impact of carbon emission trading policy on carbon emissions using a quasi-natural experiment approach. The study adopted propensity score matching combined with DID estimation to examine the environmental impact of carbon markets between 1990 and 2023 period. The results confirmed that carbon trading policies significantly reduce carbon emissions through technological innovation and energy efficiency improvements, thereby contributing to environmental sustainability. Kramer and Lessmann (2023) investigated the environmental effect of the California carbon trading system. Using panel data for all U.S. states and applying the synthetic control method, the study estimated the counterfactual emissions trajectory for California. The authors concluded that carbon markets can moderately reduce environmental pollution while maintaining economic performance during the study period. Assidi et al. (2023) examined the nexus between governance quality, shadow economy and sustainable development employing panel data for 82 countries over the period 1996– 2017. The new insight from a Dynamic Threshold Analysis (DTA) was applied, and the result reveals that increase in governance quality improves environmental quality both in the short-run and the long-run, respectively. Also, Wang et al. (2023a) evaluated the relationship between environmental degradation and political risk in ASEAN countries. Using second generation techniques, the result suggests that controlling political risk and financial risk is useful in mitigating environmental degradation in ASEAN countries. Similarly, Wang et al. (2023b) employed Two Stages Least Square (2LS) to evaluate the effect of corruption on environmental quality for commonwealth nations. The result of the study has revealed that corruption increases environmental degradation in the countries from 1995 to 2018. Moreover, Alavijeh et al. (2023) evaluated the role of institutional quality on environmental degradation in EU Countries. The authors used Method of Moments Quantile Regression (MMQR), Fully modified (FMOL) and Ordinary Least Square (OLS) methods. The results show that institutional quality improves environmental degradation in EU. Ashrab and Javed (2023) used GMM approach to identify the nexus between institutional quality, human capital and environmental degradation in BRICS countries during 1995-2021 period. Empirical analyses show that human capital and institutional quality lower the environmental degradation in BRICS. Uddin et al. (2023) revisiting the effect of institutional quality, financial development on environmental degradation in ASIAN countries. The FMOL and DOLS were used in the study, the finding indicates long run relationship between institutional quality and environmental degradation in ASIAN countries, while negative relationship between financial development and environmental degradation. Furthermore, Khan et al. (2023) employed panel ARDL to examine the impact of government effectiveness in reducing environmental degradation in CEMAC countries. The finding shows that significant and long-run relationship between regulatory quality, government effectiveness and environmental degradation in CEMAC. Asif et al. (2023) evaluated the nexus between corruption, political instability and environmental Degradation in South Asia. Using Panel ARDL approach, the authors reveal that corruption and political instability positively impact on carbon footprint and ecological footprint during 198-2018. Khalfaoui e al. (2023) examined environment-growth nexus and corruption in the MENA region using Method of Moment Quantile (MMQ) estimator approach. The authors highlight that importance of curving corruption to enable enforcement of more stringent environmental regulations. Songuo and Ndou (2023) explored impact military expenditure, governance and environmental degradation in Sub-Saharan Africa covering the data from 1999 to 2020. The GMM estimator was adopted and the finding suggests that good governance contribute to increase in environmental quality in SSA. Cosma et al. (2022) examined the effect of corruption on deforestation in Pakistan. The authors applied multiple regression and the study confirmed that corruption and shadow economy positively influence deforestation between 2006 and 2014. Adebayo et al. (2022) investigated how political risk drive environmental degradation in BRICS (i.e., Brazil, Russia, India, China, and South Africa) countries during 1990-2018 period. Evidence from MMQ methods reveals that political risk positively affects environmental degradation in BRICS. Also, Husnain et al. (2022) examined the geopolitical risk on environmental degradation from E7 countries. Augmented mean group (AMG) and Second-generation panel methods were applied, the authors reveal that there exists a long-run relationship between the variables between 2005 and 2019 period. Wang et al. (2022) examined the effect of the carbon emission trading scheme in China on corporate environmental performance. Using firm-level panel data during 2008–2019 and a time-varying difference-in-difference (DID) approach, the study found that the carbon trading policy significantly enhanced green innovation and resource allocation efficiency among regulated firms. Tian et al. (2022) assessed the emission reduction effect of China's carbon emission trading policy using provincial panel data from 2005 to 2019. The study employed a propensity score matching–difference-in-difference (PSM-DID) method to evaluate the causal impact of the policy. The empirical findings indicated that the carbon market significantly reduced carbon emissions in pilot regions compared with non-pilot regions. The study also revealed regional differences in policy effectiveness depending on industrial structure and energy consumption patterns. Zha et al. (2022) explored the relationship between emissions trading schemes and corporate carbon reduction behavior. Using a matched-pair empirical approach, the study compared firms participating in emissions trading schemes with non-participating firms. The findings indicated that companies operating under carbon markets exhibit stronger carbon-reduction initiatives and environmental responsibility, which ultimately reduces industrial emissions between 1985 and 2020.

2.2 Empirical Literature on Institutional Quality and Environmental Degradation

Daghbagi (2025) examined the moderating effect of institutional quality on structural-change–CO_2 link using cross-country panel (multi-region sample, 1990–2024, Panel interaction models (structural change variables × institutional quality) and panel ARDL models. The result reveal that institutional quality moderates how structural transformation affects emissions strong institutions steer structural change toward greener outcomes, while weak institutions amplify pollution from industrialization in thirteen African countries. Almulhim (2025) investigated the testing the impact of renewable energy and institutional quality on consumption-based CO_2 emissions in BRICS 1996–2020. Using panel cointegration and long-run panel ARDL and MG estimators, the author found that institutional quality reduces consumption-based CO_2 in BRICS and strengthens the positive effect of renewable energy on lowering emissions. Tang (2025) assessed renewable energy and institutional quality effect on carbon from Belt & Road countries. STIRPAT-type framework with Driscoll–Kraay standard errors and FMOL were employed the study reveal that institutional quality is negatively associated with CO_2 emissions better institutions and higher renewable energy share both reduce carbon emissions. Aydın (2024) examined the role of environmental technologies, institutional quality and globalization on sustainable environment in developing and developed economies. Panel OLS regressions were applied to explore the interactions between environmental technologies, institutional quality, globalization and environmental outcomes during 1995-2022 period. The finding shows that investment in environmental technologies and higher institutional quality significantly improves environmental quality (lower pollution); institutional quality amplifies the benefits of green technologies. Also, Kouton (2024) conducted thresholds to sustainability, Globalization's impact on the institutional quality -ecological footprint nexus in 49 African countries between 2002 and 2022. The dynamic panel threshold models (examines different globalization thresholds). The study found that institutional quality's effect on the ecological footprint is conditional, but this mitigation depends on passing globalization thresholds (heterogeneous effects across countries).

3.1 Theoretical Framework and Model

This study employed Pigouvian Fiscal Policy Theory to examine the nexus among carbon market, shadow economy and environmental pollution with the role of institutional quality. The environmental financing is also closely influenced by the fiscal policy framework. The extent to which taxation can be used as an instrument of environmental policy and the degree of decentralization of the taxation system effect environmental policy decisions. The Pigou (1920) recommended the use of corrective taxes to eliminate the distortive effects of negative externalities. Such taxes would be designed to adjust the marginal private costs of economic activity to include its social costs. In addition, taxes levied on measured quantities of polluting emissions are Pigouvian taxes that, when they are set right, change the behavior of polluters by internalizing external social costs.

From a theoretical perspective, carbon markets are grounded in the Pigouvian approach to environmental regulation, which emphasizes the use of economic incentives to correct market failures associated with environmental externalities. Environmental pollution is often considered a negative externality because polluting firms do not bear the full social costs of their emissions. Carbon pricing mechanisms such as emissions trading systems help internalize these externalities by imposing a cost on carbon emissions, thereby motivating firms to reduce pollution levels (Stiglitz & Stern, 2017). As a result, carbon markets promote environmental sustainability by encouraging economic agents to adopt environmentally friendly production and consumption patterns. In the Pigouvian framework, environmental externalities are explained through the relationship between marginal private cost (MPC), marginal damage (MD) and marginal social cost (MSC). However, the production activities that generate pollution often additional cost on society that are not borne by the producer. These additional costs are to as marginal damage which represent environmental and social harm caused by pollution such environmental degradation and loss of biodiversity. The theory suggests the use of corrective policies such as environmental taxes or carbon pricing to internalize the marginal damage and align private incentive with social welfare, thereby promoting environmental sustainability. The Pigouvian model is represented as;

$$ED_{it} = f(CM_{it}) \qquad 3.1$$

Where ED is the dependent variable which is environmental degradation and CM is the carbon market proposed by Pigou. Also, the Pigouvian theory suggested that lack of fiscal policies or regulations within the economy can hinder effective environmental governance and regulatory enforcement, allowing for potential environmental harm to go unchecked. The Pigouvian model is re-specified as;

$$ED_{it} = f(CM_{it}., RQ_{it}) \qquad 3.2$$

Moreover, it has been suggested that interaction of carbon market and regulatory quality (CM*RQ) might lead to lower environmental degradation because firms are compelled to reduce emission and invest in green innovation (Zhang et al., 2024). Thus, the model is re-written as;

$$ED_{it} = f(CM_{it}, RQ_{it}, CM * RQ_{it}) \qquad 3.3$$

Other factors such as energy transition and urbanization have been a critical factor that influences environmental degradation. For example, an increase in energy transition reduces the consumption of fossil fuel and gas flaring leading to eco-friendly environment. The theoretical framework of Pigouvian model is presented as;

$$ED_{it} = f(CM_{it}, RQ_{it}, CM * RQ_{it}, ET_{it}) \qquad 3.4$$

Furthermore, environmental degradation is proxied by carbon dioxide (CO_2) emission (metric tons per capita). The CO_2 emission per capita is measured by total national CO_2 emissions per year divided by total population. Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement (WB, 2025). Carbon market is a market- based environmental policy mechanism that allows governments, firms, or institutions to buy and sell carbon emission allowances in case of compliance carbon market and/or carbon credit in case of voluntary carbon market in order to off-set greenhouse gas (GHG) emission in a cost-effective way. The carbon emission credits encourage polluters to adopt cleaner technologies and climate resilient. The carbon market is measured as the total number of credits retired that has been permanently removed from circulation after being used to offset greenhouse gas emission (Voluntary Registry Offsets Database, [VROD] 2025). Regulatory quality is the ability of government to formulate, rule and implement policies and regulations that permit and promote private and public sectors development in achieving eco-friendly environment. The RQ measures on the scale of (-2.5 week; 2.5 strong), means lower or poor regulatory quality, and strong or high regulatory quality, respectively (WGI, 2025). Energy transition refers to the renewable energy derived from natural resources that are replenished and sustainable over time. Renewable energy is measured as renewable energy share as percentage of total energy consumption (WB, 2025).

4.1 Methodology

4.1.1 Cross-section Dependence Test

In panel data, where data is collected over time for multiple entities, such as countries or regions, the assumption of cross-section independence is crucial for accurate estimation of parameters and valid hypothesis testing (Greene 2012). The test evaluates whether there is correlation or interdependence among the cross-sections beyond what would be expected by chance. If cross-section dependence exists and not address, it can lead to biased estimates and inefficient inference in panel data models. Therefore, to assess the cross-sectional dependency (CD), the study employs the test proposed by Pesaran (2004) to determine the presence of any interdependence among variables within the cross-sectional units. The CD model is presented as;

$$CD_i = \frac{1}{N}\sum_{j=1}^{N} \rho_{ij} \qquad 4.1$$

4.2 Panel Unit Root Tests

After confirming the presence of cross-sectional dependency in a panel of countries through Pesaran (2004) CD test, this study employed the Cross-Sectional Augmented Dickey-Fuller (CADF) panel unit test introduced by Pesaran (2007) and Cross-Sectional Im Pesaran and Shin (CIPS) panel unit test proposed by Im, Pesaran, and Shin (2003) to check the stationarity properties of the variables.

4.2.1 Cross-Sectional Augmented Dickey-Fuller (CADF) Panel Unit Test

The CADF test specifically considers cross-section dependence among variables and evaluates the null hypothesis of cross-sectional dependency in a panel of countries. Its primary goal is to ensure that, even in the presence of cross-sectional dependency, the variables are either stationary at the level ($I(0)$) or exhibit first-order differences ($I(1)$). The rule of thumb for rejecting the null hypothesis of non-stationarity in the CADF test involves comparing the computed test statistic with critical values (Pesaran (2007). For a panel variable Y_{it}, CADF regression equation is represented as

$$\Delta Y_{it} = \alpha_i + b_i y_{it-1} + c_i \acute{y}_{t-1} + d_i \Delta \acute{y}_{t-1} + \sum_{j=1} \delta ij \, \Delta y_{it-1} + \varepsilon_{it} \qquad 4.2$$

i. Ho: b_i =0 (unit root, nonstationary)

ii. H_1: $b_i < 0$ (Stationary)

4.2.2 Cross-Sectional Im Pesaran and Shin (CIPS) Unit Root Test

The Cross-Sectional Im Pesaran and Shin (CIPS) unit root test is also a commonly used method to assess stationarity in panel data with cross-sectional dependence. This test, proposed by Im, Pesaran and Shin (2003) extends the Augmented Dickey-Fuller (ADF) test to account for cross-sectional correlation. The null hypothesis of the CIPS test is that the panel series has a unit root, indicating non-stationarity. If the calculated test statistic is greater than the critical value, the null hypothesis of a unit root is rejected, indicating stationarity. Therefore, the CIPS statistics is written as;

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} ti \text{ CADF} \qquad 4.3$$

Where; t^{CADF} = the statistics on bi from the CADF regression, and N is number of cross-sectional units.

4.3 Panel Cointegration Test

After establishing the order of integration of the variables, Westerlund (2007) cointegration test is employed. Westerlund (2007) proposed a cointegration test that addresses some limitations associated with other panel cointegration tests, such as Kao (1999) and Pedroni (2004). The superiority of Westerlund's cointegration test lies in its ability to consider both the common factor and cross-sectional dependence in the data, making it more robust under various conditions. The model specification for the Westerlund (2007) cointegration test involves regressing the first-differenced variables on their own lags and the levels of the variables:

$$\Delta Y_{it} = \alpha + \sum_{k=1}^{p} \beta_k \, \Delta Y_{it-k} + \sum_{l=0}^{q} \gamma_{;t} \, \Delta Y_{it-l} + \varepsilon_{it} \qquad 4.4$$

where: Yit is the level of the variable for country i at time t, ΔYit is the first difference of Yit, α is the intercept, βk represents the coefficients of the first-differenced lags, γit represents the coefficients of the levels, and εit is the error term.

4.4 Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) Model

This study employs the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model developed by Chudik and Pesaran (2015) to examine the effects of carbon market, renewable energy transition, regulatory quality, and the interaction between regulatory quality and carbon market on carbon dioxide emissions in 13 Sub-Saharan African (SSA) countries over the period 2009–2024. The selection of the CS-ARDL estimator is motivated by several econometric and theoretical considerations. First, the selected SSA countries are economically, politically, and environmentally interconnected through regional trade, investment flows, climate agreements, and technology diffusion. Consequently, shocks occurring in one country such as changes in global oil prices, climate policies, financial crises, or renewable energy innovations are likely to affect other countries simultaneously. This creates cross-sectional dependence, which violates the independence assumption of traditional panel estimators. The CS-ARDL model addresses this

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problem by augmenting the regression with cross-sectional averages of both the dependent and explanatory variables, thereby controlling for unobserved common factors. Second, the variables employed in this study exhibit a mixture of integration orders, with some variables being stationary at levels, I(0), while others become stationary after first differencing, I(1). Conventional panel cointegration techniques such as Panel Panel ARDL, FMOLS and Panel DOLS generally require all variables to be integrated of the same order, usually I(1). In contrast, the CS-ARDL estimator accommodates a mixture of I(0) and I(1) variables provided none is integrated of order two, I(2), making it particularly suitable for this study (Chudik & Pesaran, 2015).

Therefore, the CS-ARDL estimator simultaneously estimates both short-run dynamics and long-run equilibrium relationships within a single framework through the error correction representation. This allows the study to distinguish between the immediate effects and the persistent long-term impacts of carbon market development, renewable energy transition, and regulatory quality on environmental quality. Following Chudik and Pesaran (2015), the general CS-ARDL model is specified as:

$$\Delta Y_{it} = \sum_{j=1}^{p} \Theta_{ij}\, Y_{it-j} + \sum_{j=0}^{q} \beta_{;j}\, X_{it-j} + \sum_{j=0}^{r} Y_j\, \bar{\mathrm{Y}}_{it-j} + \sum_{j=0}^{s} \sigma_j\, \chi_{it-j} + \mathrm{U}_i + \varepsilon_{it} \qquad 4.4$$

The CS-ARDL error correction model estimated in this study is:

$$\Delta lnCO2PC_{it} = a_i + \curlywedge_i\, ECM_{it-1} + \sum \Theta_j \Delta X_{it-j}\ \sum \psi_j \Delta\hat{Z}_{it-j} + \varepsilon_{it} \qquad 4.5$$

4.5 Result and Discussion

Prior to empirical investigation of the effect carbon market, shadow economy and environmental sustainability with the role of institutional quality in panel data from 2009 to 2024. The study explores the nature or characteristics of the variables under consideration. The result from Table 1 reveal that the mean values of CO_2 emission in SSA countries are 1.016. This provides a baseline measure of the environmental impact in the region. In terms of carbon market, the average carbon projects retired in the region is 126314 between 2009 and 2024, reflecting the performance of carbon trading across the countries.

Table 1: Result of Panel Summary Statistics

Variables	CO2PC	CM	RQ	RE	RQ*CM
Mean	1.0164	126314	-0.715	74.568	-8.82833
Median	0.3437	4828	-0.633	81.35	-7.55961
Maximum	8.8711	99545	0.4491	97	6.051523
Minimum	0.0824	376	-2.369	7.6	-29.5646
Std. Dev.	2.0639	18095	0.5930	22.929	6.983709
Skewness	3.0682	2.2836	-0.981	-1.879	-0.79171
Kurtosis	10.816	8.541	4.0508	5.712	3.791249
Jarque-Bera	847.60	442.607	42.570	184.41	26.89413
Probability	8.80185	7.75	5.70	9.03	1.45E-06

Observations	202	202	202	202	202

Sources: Authors' computation (2026).

In addition, in the case of regulatory quality (RQ), the maximum value of 0.4491 score suggests the highest level of regulatory effectiveness, while the minimum value of -2.369 score indicates the lowest. The standard deviation of 0.5930 score reflects the variability in regulatory quality within the sampled countries. Skewness measures the asymmetry of the distribution, while kurtosis reflects the tail behavior. The skewness value of 3.0682 for CO_2 emission indicates that the distribution is positively skewed to the right, suggesting a longer right tail. The kurtosis value of 10.816 indicates leptokurtic behavior, meaning the distribution has heavy tails and is more peaked than a normal distribution.

4.5.1 Result of Pesaran (2004) Cross-section Dependence Test

The results of Pesaran (2004) cross-section dependence test presented in table 2 show that all variables have p-values less than 0.05, suggesting strong evidence to reject the null hypothesis. Therefore, the study concluded that there is significant cross-sectional dependence among the cross-sectional units,

Table 2: Results of Pesaran (2004) Cross-section Dependence Test

Variables	Statistic	Prob.
CO_2	10.7779	0.000
CM	11.6524	0.000
RQ	0.7787	0.000
RQ*CM	20.2126	0.000
RE	12.8230	0.000

Note: Null hypothesis: No cross-section dependence (correlation). Source: Researchers' Computation (2026).

4.5.2 Results of Panel Unit Root Tests

After confirming the presence of cross-sectional dependence, this study utilized panel unit root tests that consider cross-sectional dependency when determining the order of integration. The two tests employed in this study to assess the stationarity status of the variables are the CADF and CIPS panel unit root tests.

The results of these tests are presented in Table 3. The outcomes of the CADF and CIPS panel unit root tests, as displayed in table 3, indicate that all variables exhibit a unit root at their level, signifying non-stationarity except regulatory quality, renewable energy and RQ*CM which they are stationary at level. Nevertheless, upon taking the first difference, they become stationary and therefore, integrated to order of (I[1]).

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Table 3: The CADF and CIPS Unit Root Tests Results

	CADF-Test		CIPS-Test		
Variables	Level	First difference	Level	First difference	Stationary Status
$lnCO_2$	-1.715	-2.990***	-2.5704	-6.6338***	I(1)
LnCM	-2.004	-2.730***	-2.26215	-5.0001***	I(1)
RQ	-2.595***	________	-1.4122*	_________	I(0)
LnRE	-2.161*	________	-2.359*	_________	I(0)
RQ*CM	-3.360***	---------_____	-4.4224***	-----------	I(0)

Source: Authors' calculation (2026). **Note**: ***, **, & * indicates 1%, 5% and 10% level of significant.

This implies the rejection of the null hypothesis that all panels contain unit roots. Consequently, it can be inferred that all the variables are stationary either at level I(0) or at first difference [I(1)]. This justified the employment of CS-ARDL to examine the short-run and long-run relationship among the variables in the study.

4.5.3 Results of Panel Cointegration Tests

Following the determination of the integration order of the variables, the Westerlund (2007) test for cointegration is employed to examine the presence of a cointegration (long-run) relationship among the variables specified in the models.

Table: 4: Result of Westerlund (2007) Panel Cointegration

	Model (CO_2=lnCM, RQ, RQ*CM, lnRE)
Variance ratio	3.7234
P-values	0.0001***

Note: Null hypothesis: No cointegration, ***p < 0.01, **p < 0.05, time trend included. **Source:** Researchers' Computation (2026).

The outcomes of this test are presented in Table 4. reveal long-run cointegration among the variables. This signifies the rejection of the null hypothesis, suggesting the existence of a cointegration (long-run) relationship among the variables in the specified models.

4.4 Results For CS-ARDL Model

The results of the CS-ARDL estimation presented in Table 5, provide insight into the determinants of environmental sustainability, proxied by CO_2 emissions, in Sub-Saharan African (SSA) countries. The model examines the role of carbon market performance and regulatory quality on environmental sustainability a long with energy transition. For instance, the short-run result implies that a 1% increase in the total value of carbon credit retirements in Sub-Saharan Africa's voluntary carbon market is associated with a 0.07% increase in per capita CO_2 emissions in the region. This revalidates evidence of baseline manipulation and integrity flaws in the region's voluntary carbon offset market. Until recently, the market was dominated by avoidance projects relying on counterfactual baselines rather than actual carbon removal and reduction projects; thus, less likely to reduce emissions per person (CO_2). As such, credits were issued for actions that would have happened anyway, failing to deliver real climate mitigation. This creates systematic over crediting, meaning credits are issued for emission reductions or removals that do not actually exist, undermining the credibility of the voluntary carbon market. For example, Kariba REDD+ Project in Zimbabwe: Lake Kariba, October 2023. South Pole terminates the Kariba REDD+ project after investigations show baselines inflated five- to tenfold, tens of millions of credits retired by Gucci, Volkswagen, McKinsey, and Nestlé against work that did not happen, and the host community receiving a fraction of global revenue.

Further, Independent carbon-crediting analyses and independent rating agencies have downgraded or flagged a significant portion of nature-based and forest protection offsets in Africa for utilizing non-conservative baseline assumptions that overstate the imminent risk of tree clearing. These inflated counterfactuals set baseline emissions or deforestation rates artificially high so that any minor conservation or reduction effort claims massive, unearned credit volumes.

Additionally, the coefficient energy transition is negative and highly significant. This means that A 1% increase in renewable energy transition reduces CO_2 emissions by 2.23% in the short run. This finding is consistent with environmental theory that greater use of solar energy, wind, hydroelectricity, biomass, reduces dependence on fossil fuels. SSA countries increasingly invested in renewable energy after 2010 through: solar mini-grids, hydropower, international climate finance. Regulatory quality is found to be negative but insignificant in influencing CO_2 emissions in SSA region. Better regulatory quality tends to reduce pollution, but across the 13 SSA countries, the effect is not statistically influenced the emission reduction in the region. This might be due to weak institutional capacity, inconsistent policy implementation, corruption, poor enforcement of environmental regulations, political instability. Therefore, improvements in regulatory quality alone have not significantly off-set emissions in the short run. The result also reveals that there is positive and insignificant relationship among the interactive effect of regulatory quality and carbon market on CO_2 emissions in the short-run. The insignificant interaction suggests that regulatory quality does not significantly strengthen or weaken the impact of carbon markets on CO_2 emissions. This implies that even where regulatory quality is relatively better, it has not yet enhanced the effectiveness of carbon market policies during the study period. Possible reasons include immature carbon markets, inadequate institutional coordination, weak environmental governance and limited or proper compliance in the region.

Table 5: Results of CS-ARDL Estimated Coefficients (DV=lnCO2)

Panel A: Long-Run CS-ARDL ---------------------------DV= $\ln CO_2$ emissions				
Variables	Coefficient	Standard Error	Z-value	P-value
LnCM	-0.924132***	0.03878	-23.82	0.0000
lnRE	-2.35033**	0.836935	-2,81	0.005
RQ	-2.300046	1.81821	-1.26	0.206
RQ*CM	0.187224	0.150311	1.25	0.213
Panel B: Short-Run CS-ARDL ---------------------------DV=$\Delta\ln CO_2$ emissions				
ΔlnCM	0.075867	0.038788	1.96	0.050
ΔlnRE	-2.22588	0.801940	-2.78	0.006

ΔRQ	-1.46152	1.256457	-1.16	0.245
ΔRQ*CM	0.118629	1.16620	1.17	0.244
R-square (MG)	0.93			
RMSE	0.05			
Observation	202	202	202	202

Source: Authors' computation (2026).

Moreover, the long-run results imply that the long-run impact of a change in InCM on $InCO_2$ has essentially no lagged effects. The long run change is very close to being equal to the initial change (the coefficient is close to one). However, the long run result (- 0.924132) implies that, with the recent shift in the SSA's voluntary carbon market toward carbon emissions removal and direct reduction rather than avoidance, change in InCM would tend to have significant negative effect on CO_2 in the long run. The statistical significance of the coefficient confirms that this relationship is not due to random variation, implying that carbon market mechanisms play an important role in improving environmental quality over time. The negative relationship suggests that the expansion and effective implementation of carbon market mechanisms contribute significantly to reducing carbon emissions across SSA countries. Carbon markets place an economic cost on greenhouse gas emissions, encouraging firms to adopt cleaner production technologies, improve energy efficiency, and invest in renewable energy sources. In addition, the long-run result indicated that there is negative and significant impact of energy transition with zero long-run lag effects on CO_2 emissions in the SSA countries. That is, the coefficient energy transition is far away from being equal to one (2.35%) in the long run. However, the long-run effect is slightly larger than the short-run effect, indicating that renewable energy investments become more effective over time as infrastructure expands, technologies mature, and dependence on fossil fuels declines without lag effect on CO_2 emissions. In addition, the coefficient of regulatory quality (-2.300) is statistically insignificant suggesting that although better regulatory quality appears to reduce emissions, the evidence suggests that governance improvements alone have not consistently translated into measurable long-run emission reductions across the sampled countries.

The long-run interactive effect of regulatory quality and carbon market is found to be positive and not significant in affecting CO_2 emissions in SSA countries. This indicates that regulatory quality does not significantly modify the long-run relationship between carbon markets and CO_2 emissions. Carbon market effectiveness likely depends on additional factors such as market maturity, institutional capacity, emissions monitoring, and broader climate policy frameworks. This finding suggests that regulatory quality does not significantly moderate the relationship between carbon markets and carbon emissions within the study period. The implication is that existing regulatory institutions have not been sufficiently strong to enhance the effectiveness of carbon market mechanisms in reducing emissions.

Finally, the error correction coefficient is negative (-0.90) and statistically significant at the 1% level. This confirms the existence of a stable long-run equilibrium relationship among the variables. The coefficient further indicates that approximately 90% of short-run disequilibrium is corrected within one year, suggesting a very rapid speed of adjustment toward long-run equilibrium. The overall goodness-of-fit statistics indicate that the estimated CS-ARDL model provides a satisfactory explanation of the relationship between carbon market development and CO_2 emissions in Sub-Saharan Africa. The adjusted R-squared value of 0.93 indicates that approximately 93% of the variation in CO_2 emissions across the sampled Sub-Saharan African countries is explained by the explanatory variables included in the CS-ARDL model, after adjusting for the number of regressors. This suggests that the model has excellent explanatory power and that the selected variables, including the carbon market, renewable energy transition, regulatory quality, and their interaction effects, jointly explain most of the long-run and short-run variations in environmental degradation. The high adjusted R-squared also indicates that the inclusion of additional explanatory variables has not artificially inflated the explanatory power of the model, making the results reliable and robust. The overall R-squared value of 0.39 implies that approximately 39% of the total variation in CO_2 emissions is explained by the regressors without adjusting for model complexity. Therefore, an R-squared of 0.39 does not indicate poor model performance but rather reflects the heterogeneous nature of the sampled economies. The Root Mean Square Error (RMSE) of 0.05 indicates that the average prediction error of the estimated model is very small. Specifically, the predicted values of CO_2 emissions deviate from the observed values by only about 0.05 units on average. Thus, the RMSE value suggests that the CS-ARDL model fits the data well and produces reliable estimates of the relationship between carbon market development and environmental degradation in Sub-Saharan Africa.

5.1 Conclusion and Policy Recommendations

The CS-ARDL results indicate that carbon market and renewable energy transition are the only variables with a statistically significant and environmentally beneficial effect on CO_2 emissions in both the short run and the long run. Regulatory quality and its interaction with carbon markets are not statistically significant, implying that governance reforms alone have not been sufficient to reduce emissions or enhance the effectiveness of carbon markets over the study period. Overall, the findings suggest that SSA countries should prioritize accelerating issuance of carbon credits for renewable energy projects, particularly by national registries. While regulatory quality is found to be weak and insignificant in enhancing environmental quality. Therefore, based on the findings, the study recommends the following: first, government should strengthen carbon market institutions by developing transparent legal and regulatory frameworks that enhance the credibility and effectiveness of emissions trading systems. That is, expanding carbon pricing mechanisms across more sectors of the economy, particularly energy, manufacturing, transportation, and extractive industries, where emissions are highest. Second, governments should prioritize renewable energy investments through increased public expenditure, tax incentives, subsidies, and improved access to climate finance. Rural electrification projects should increasingly rely on renewable energy technologies to reduce dependence on fossil fuels. Third, governments should prioritize strengthening institutional capacity, enforcement mechanism, and sector-specific environmental laws rather than relying solely on general improvement of regulatory quality in the region. Finally, the SSA governments should strengthen institutional quality before expecting carbon market to effectively off-set emission in the region. Regional carbon market integration and sector-specific pilot programs may be needed to achieve the scale and credibility required for the interaction to become significant in off-setting emissions in the region.

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