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Effect of Carbon Footprint on Agricultural Productivity in Nigeria: An Empirical Analysis

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ABSTRACT

This study examines the relationship between carbon footprint (CFP) components and agricultural productivity in Nigeria, a critical area of investigation given the country's reliance on agriculture for economic stability, food security, and employment. Using time series data from 1990 to 2020, sourced from the Central Bank of Nigeria (CBN) and the World Bank, this study analyzes the effect of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions on agricultural output. Employing Robust Least Square (RLS) regression and the Error Correction Model (ECM), the study finds that CO_2 and CH_4 emissions negatively affect agricultural productivity, with 1% increases in CO_2 and CH_4 emissions leading to approximate decreases in agricultural output by 2% and 3%, respectively. Conversely, a 1% increase in N_2O emissions correlates with an 8% increase in agricultural output, attributed to the use of nitrogen-based fertilizers. The results confirm the presence of long-run equilibrium relationships among the variables, with approximately 32% of the previous year's disequilibrium corrected annually. The study's findings align with the Environmental Kuznets Curve (EKC) hypothesis, suggesting that Nigeria is in the early stages of economic growth where environmental degradation is pronounced. These insights underscore the need for sustainable agricultural practices and effective carbon emission mitigation strategies to enhance food security and support economic growth in Nigeria.

JEL Classification Code: Q00, Q1, Q56, C32

Keywords: Agricultural Productivity, Carbon Footprint, Carbon Dioxide (CO_2) Emissions, Methane (CH_4) Emissions, Nitrous Oxide (N_2O) Emissions, Environmental Kuznets Curve (EKC), Nigeria, Sustainable Agriculture

1. Introduction

The interplay between carbon footprint and food production is a critical area of investigation, especially in developing nations like Nigeria where agriculture remains a cornerstone of the economy. The ecological footprint, encompassing resource use and carbon dioxide absorption by the environment, is heavily influenced by carbon emissions, which constitute over 50% of the ecological footprint globally (Global Footprint Network, 2018). This dynamic significantly affects food production, as agriculture both impacts and is impacted by environmental conditions (Pegels and Altenburg, 2020). Addressing carbon footprints (CFP) while maintaining robust food production is crucial, particularly as global food demand is projected to rise with population growth (United Nations (UN), 2019). Agricultural practices are a major contributor to climate change, accounting for substantial greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Tubiello *et al.*, 2021; Intergovernmental Panel on Climate Change (IPCC), 2022).

Carbon footprint in form of emissions result from various agricultural activities such as livestock rearing and fertilizer application, which, while boosting yields, also exacerbate greenhouse gas accumulation (Balsalobre-Lorente *et al.*, 2019). The increasing pressure on agricultural systems to meet food demand has led to the overuse of resources, thereby intensifying environmental degradation and emissions (Food and Agriculture Organization (FAO), 2021). In Nigeria, agriculture is vital for economic stability, food security, and employment, supporting the majority of the population (Alege *et al.*, 2017). However, the sector faces significant challenges due to climate change, manifesting in crop failures, hunger, and malnutrition. Hence, this study explores the relationship between CFP and food production in Nigeria, aiming to understand the extent of this effect and provide insights into sustainable agricultural practices. This study utilises time series data spanning from 1990 to 2020, sourced from the Central Bank of Nigeria (CBN) and the World Bank. The chosen timeframe encompasses the period during which the concept of CFP gained broader recognition, extending the analysis slightly backward to provide comprehensive insights.

This study is crucial for multiple reasons. Firstly, the agricultural sector is a significant contributor to Nigeria's Gross Domestic Product (GDP) and a primary source of livelihood for a large portion of the population. By ensuring that agricultural practices are sustainable and productive, the study supports broader economic stability and growth. This is particularly important in the face of climate change, which poses a threat to agricultural output and, consequently, the economy. Secondly, with the population projected to increase substantially, ensuring food security is a critical concern. This study helps identify how CFP affects food production and suggests ways to mitigate these effects, thereby contributing to the goal of achieving zero hunger and enhancing food security. Lastly, the research highlights the importance of reducing carbon emissions to combat climate change. The study promotes conservation efforts that are vital for maintaining ecological balance by emphasising the environmental benefits of sustainable agricultural practices.

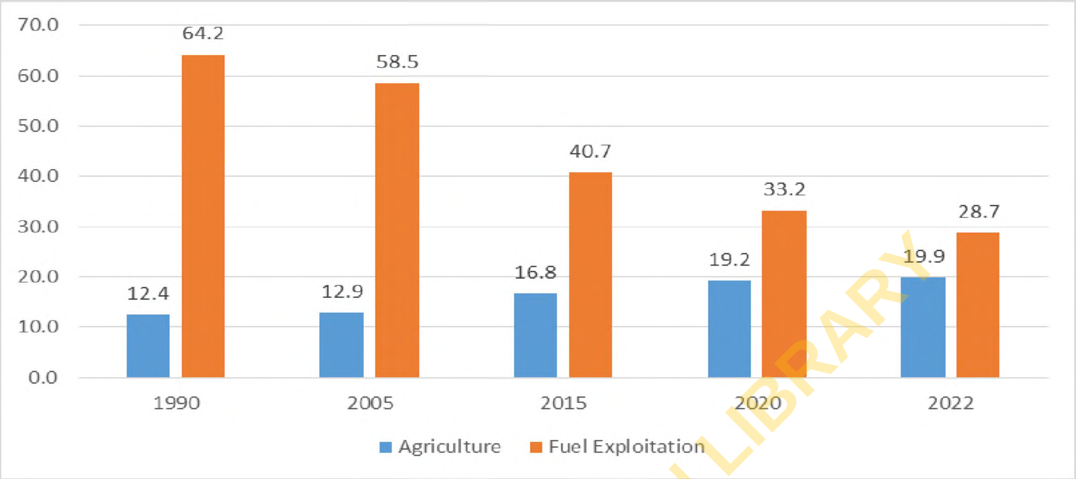
2. Conceptual Background

The vision of the Food and Agriculture Organization (FAO) is to create a world without hunger, where everyone has access to the food needed for a healthy and active life (FAO, 2022). However, the current environmental footprint (EFP) of humanity is unsustainable. Through various land uses for agriculture and other anthropogenic activities, humans have significantly transformed the earth's landscape, increased resource use, and generated substantial waste. Hu *et al.* (2019) highlighted that the actual ecological footprint of humanity far exceeds the sustainable limits, indicating a critical need for sustainable practices. Food and agriculture are essential components of human well-being and are central to civilisation, which began with the advent of agriculture around 8000 BC (Lal, 2022). Agriculture and food systems are major consumers of natural resources, utilising over 40% of ice-free land and 70% of freshwater resources for irrigation (Lal *et al.*, 2021). Despite their importance, these systems also contribute significantly to environmental degradation, with agricultural activities being major sources of GHG emissions (IPCC, 2019). These emissions account for 25%-30% of all anthropogenic emissions and are increasing at a rate of 1% per year.

The main sources of GHG emissions in Nigeria include land-use changes, forestry, energy, waste, and agriculture. From the viewpoint of greenhouse gas emissions by sector in Nigeria, statistics from the Joint Research Centre/the International Energy Agency (JRC/IEA, 2023) indicated that fuel exploitation and agriculture are the first two sectors responsible for GHG emissions. Incidentally, while the proportion of GHG emissions by fuel exploitation declined from 64.2 percent in 1990 to 28.7 percent in 2022, the proportion of GHG emissions by agriculture rose from 12.4 percent in 1990 to 19.9 percent in 2022 (See Figure 1). One plausible explanation for this observed trend of emissions by the two leading sectors is the trend of population figure in Nigeria for the selected years. The population figure moved from 95.270million in 1990 to 216.844million in 2022 (JRC, 2023).

CFP, a subset of EFP, represents the total GHG emissions from human activities, expressed as CO_2 equivalent. The CFP of agricultural products can constitute more than 50% of their total EFP (Balogh, 2019). Addressing the CFP while maintaining robust food production is essential, particularly as global food demand is projected to rise with population growth (UN, 2019).

Proportions of GHG Emissions by Fuel Exploitation and Agriculture in Nigeria: 1990-2022



Source: Underlying Data obtained from the Joint Research Centre and the International Energy Agency Emissions Database for Global Atmospheric Research (2023).

3. Empirical Review

Recent empirical studies have explored the dynamic relationship between carbon emissions, climate change, and agricultural productivity, particularly to Nigeria. These studies provide a comprehensive understanding of how environmental factors influence agricultural outcomes, contributing to the broader discourse on sustainable development. Amaefule *et al.* (2023) examined the effect of climate change on agricultural productivity in Nigeria through the carbon emissions channel. Utilizing the transposed second-generation environmental Kuznets curve model and data from the World Development Indicators spanning from 1960 to 2019, the study employed the autoregressive distributed lag (ARDL) method. The findings revealed a long-run relationship between carbon emissions (proxied by CO_2 emissions and CO_2 intensity) and agricultural productivity (measured by agricultural GDP, crop production index, and food production index). The results indicated that CO_2 emissions and intensity negatively impacted crop and food production, thereby posing a threat to agricultural productivity and food security in Nigeria.

Opeyemi *et al.* (2022) focused on the influence of CO_2 emissions on cereal yields in Nigeria from 1961 to 2018. Using secondary data from FAOSTAT and applying ARDL, the study found a negative short-run relationship between carbon emissions and cereal yields. However, in the long run, the relationship turned positive, indicating complex dynamics between carbon emissions and cereal crop performance. Adeleye *et al.* (2021) explored the effect of environmental degradation, proxied by carbon emissions, and non-renewable energy on agro-productivity in Nigeria using annual data from 1980 to 2018. The study employed the Johansen cointegration and impulse response functions within a vector autoregressive framework. The results revealed that carbon emissions significantly reduced agro-productivity, while non-renewable energy positively impacted agro-productivity. Additionally, factors such as domestic credit, rural population, and arable land exhibited asymmetric effects on agro-productivity.

Mrówczyńska-Kamińska *et al.* (2021) conducted a study on GHG emissions intensity of food production systems and its determinants across 14 countries, accounting for over 65% of global food production between 2000 and 2014. The study found a decrease in emission intensity from more than 0.68 kg of CO_2 equivalent per USD 1 worth of food production in 2000 to less than 0.46 in 2014. The key determinants of reduced emission intensity included increased cereal yields, the use of nitrogen fertilizers, agricultural material intensity, the Human Development Index, and the share of fossil fuel energy consumption. Jeremias (2019) explored agriculture-specific determinants of CFP on a global scale, using data from 1961 to 2013. The study employed feasible generalized least squares estimator and panel unit root tests, revealing that economic development and agricultural production (including arable land, agricultural machinery, and fertilizer use) stimulated CFP. Conversely, a higher share of the rural population and agricultural development negatively influenced the growth of CFP.

4. Theoretical Framework

The theoretical underpinning of this study is rooted in the Environmental Kuznets Curve (EKC) hypothesis. The EKC hypothesis, initially proposed by Simon Kuznets in 1966 to study income inequality, was later adapted by researchers to examine the environmental impact of economic development. The EKC hypothesis suggests that the relationship between environmental degradation and economic growth follows an inverted U-shape curve (Tenaw & Beyene, 2021). This implies that at early stages of economic growth, environmental degradation and pollution increase, but after reaching a certain level of income per capita, the trend reverses, and further economic growth leads to environmental improvement. EKC categorizes economic growth into three stages:

The first stage, known as the scale effect stage, is associated with the early phase of economic development (Kejak, 2003). During this period, countries focus primarily on economic performance with minimal regard for environmental consequences (Bibi & Jamil, 2021). Hence, developing economies at this stage prioritize rapid economic growth and industrialization, driven by a competitive ideology aimed at catching up with developed nations. This emphasis on economic expansion often results in significant environmental degradation due to the extensive use of natural resources and increased pollution levels (Mahmood, 2023). Environmental regulations and sustainable practices are typically overlooked, leading to adverse environmental impacts.

The second stage, referred to as the technological expansion effect stage, marks a transitional phase where awareness of environmental and health impacts begins to grow (Mahmood *et al.*, 2023). As the negative consequences of environmental degradation become more evident, there is a societal shift towards advocating for better environmental quality. This stage is characterized by the implementation of structural programs aimed at reducing pollution and promoting sustainable practices (Ahmad *et al.*, 2021). The relationship between economic growth and environmental quality starts to improve as cleaner technologies and environmentally friendly practices are adopted. Industries begin to innovate, incorporating technologies that reduce emissions and waste, balancing economic growth with environmental preservation.

The final stage, the composite effect stage, represents an advanced phase of economic development where full awareness and implementation of sustainable economic practices are observed (Udemba, 2020). At this stage, economic operations are highly advanced, incorporating clean technologies that ensure both economic growth and environmental sustainability. The service sector and research and development programs play a crucial role in driving technological innovation and adopting renewable energy sources (Fang *et al.*, 2022). There is a strong emphasis on environmental conservation, and economic activities are designed to minimize their environmental footprint. This stage reflects a mature economy where economic and environmental goals are aligned, leading to improved environmental quality and sustainable development.

The application of the EKC hypothesis to this study is particularly relevant for assessing the environmental footprint of Nigeria. As a developing country, Nigeria is primarily in the initial stage of economic growth, striving to transition to a more sustainable development pathway. By investigating the EKC hypothesis in the context of Nigeria, this study aims to contribute to the understanding of how economic development stages affect environmental quality.

5. Methodology

The study utilizes time series data drawn from the publications of CBN and the World Bank. The dataset covers the period from 1990 to 2020, capturing variables such as CFP measures (CO_2, CH_4 and N_2O) and agricultural sector output. The choice of this period is based on the increasing relevance and data availability of CFP from the 1990s onward. To achieve the objective of this study, different econometric models were adopted. The Robust Least Square (RLS) regression model was employed to identify the determinants of CFP on food production. The Ordinary Least Squares method, although commonly used to show linear relationships among stochastic variables, is often not robust due to underlying assumptions (Cassel *et al.*, 1999). Violations of these assumptions can lead to misleading results. Therefore, the RLS model, designed to be less affected by such violations, uses the M-estimation technique (a maximum-likelihood type method) to provide more reliable estimates. The RLS regression model is specified as follows:

$$\Delta ln\ AGRIC_t = \alpha + \beta\, \Delta ln\ CO_{2t} + \gamma\, \Delta lnCH_{4t} + \lambda\, \Delta ln\ N_2O_t + \mu_i \ldots\ldots\ldots\ldots (1)$$

Where;

AGRIC = Agricultural sector output

CO_2 = carbon dioxide (proxy for CFP)

CH_4 = Methane (proxy for CFP)

N_2O = nitrous oxide (proxy for CFP)

Δ = difference operator

α = intercept parameter

β, γ, and λ = partial slope parameters.

μ_i = error term

This model helps in understanding the relationship between CFP determinants and agricultural output. Additionally, to analyze the long-run relationship between carbon footprint and food security, the Error Correction Model (ECM) was employed. The ECM is useful for determining the short-term dynamics and long-term equilibrium relationships among the variables. It incorporates an error correction term that adjusts for deviations from the long-run equilibrium. The general form of the "unrestricted" ECM, as proposed by Pesaran *et al.* (2001), is specified as follows:

$$\Delta \ln Y_t = \alpha_{0y} + \sum_i^n \alpha_{yi}\, \Delta \ln Y_{t-i} + \sum_i^n \alpha_{yi}\, \Delta \ln Y_{it-i} + \beta_1 \ln X_{it-1} + \beta_2 \ln X_{it-1} + \mu_i \ldots\ldots\ldots (2)$$

Where;

Δ = first difference operator,

α = the short-term dynamic coefficients of the model

β= the long-run effects

μ_i= error term of the model

This model allows for the estimation of both short-term and long-term effects of CFP on food security.

6. Result

6.1 Robust Least Square Regression

The coefficient for CO_2 is -1.979824, which is statistically significant with a p-value of 0.0279 as shown in Table 1. This negative coefficient suggests that an increase in CO_2 emissions is associated with a decrease in agricultural output. Specifically, a 1% increase in carbon dioxide emissions leads to an approximate 2% decrease in agricultural output. This relationship highlights the detrimental impact of CO_2 emissions on food production, likely due to the adverse effects of increased atmospheric CO_2 on crop yields and agricultural productivity. Similarly, Table 1 shows that the coefficient for CH_4 is -2.745198, with a p-value of 0.0307, also indicating statistical significance. Specifically, a 1% increase in methane emissions results in an approximate 3% decrease in agricultural output. The negative coefficient for CH_4 suggests that higher methane emissions correlate with lower food production. Methane, a potent GHG, can exacerbate climate change effects, leading to unfavorable growing conditions and reduced agricultural productivity.

The coefficient for N_2O is 8.030773, which is highly significant with a p-value of 0.0000 as presented in Table 1. In contrast to CO_2 and CH_4, the positive coefficient for N_2O indicates that increases in nitrous oxide emissions are associated with higher agricultural output. Specifically, a 1% increase in nitrous oxide emissions results in an approximate 8% increase in agricultural output. This result can be attributed to the use of nitrogen-based fertilizers, which contain nitrous oxide, to enhance soil fertility and boost crop yields. However, it is important to note that while N_2O can improve agricultural productivity, it also contributes to greenhouse gas emissions and environmental degradation if not managed properly. The R-squared value is approximately 72% as shown in Table 1, suggesting that the model explains a substantial proportion of the variation in food production. The ability of the model to explain a substantial portion of the variation in food production highlights its robustness and the significance of the included variables in affecting agricultural outcomes.

Table 1: Robust Least Square (RLS) Regression Model

Variable	Coefficient	Std. Error	z-Statistic	Prob.
C	-18.90572	14.77961	-1.279176	0.2008
LCO_2	-1.979824	0.900324	-2.199012	0.0279
LCH_4	-2.745198	1.270346	-2.160984	0.0307
LN_2O	8.030773	0.509817	15.75228	0.0000

Robust Statistics			
R-squared	0.723570	Adjusted R-squared	0.692855
Rw-squared	0.959901	Adjust Rw-squared	0.959901
Akaike info criterion	46.57455	Schwarz criterion	53.03228
Deviance	3.692113	Scale	0.306522
Rn-squared statistic	462.6855	Prob(Rn-squared stat.)	0.000000
Non-robust Statistics			
Mean dependent var	8.272991	S.D. dependent var	1.729624
S.E. of regression	0.448493	Sum squared resid	5.430953

Source: Computed by Author.

6.2 Error Correction Model

To ascertain the stationarity of the data the Augmented Dickey-Fuller (ADF) test was carried out and the result is presented in Table 2. All the variables were non-stationary at levels, except for the agriculture variable (LAGRIC) as shown in Table 2. However, at the first difference, the remaining variables become stationary, indicating a mix of integration orders, I(0) and I(1) as presented in Table 2. This necessitates testing for co-integration using the bound test due to the presence of unit roots in the series.

Table 2: Unit Root Test of Stationarity

Variables	ADF Levels	5% significant Level	ADF 1st Difference	5% significant Level	Order of Stationarity
LAGRIC	-3.390324[5]	-2.963972[5]**			**I (0)**
LCO_2	-2.406030[5]	-2.963972[5]	-5.655511[5]	-2.967767[5]**	**I (1)**
LCH_4	-1.591037[5]	-2.963972[5]	-4.515476[5]	-2.967767[5]**	**I (1)**
LN_2O	-0.492885[5]	-2.963972[5]	-6.640477[5]	-2.967767[5]**	**I (1)**

** indicates significant at 5%
[5] Indicates that a maximum lag length of 5 was included in the tests.
Source: Computed by the Author

The result of the Bound test, presented in Table 3, indicates a co-integrating relationship as the F-statistic (10.40140) is greater than the critical values for the upper bound at a 5% significance level. Hence, the null hypothesis of no co-integration is rejected, affirming the existence of a long-run equilibrium relationship among the variables.

Table 3: Result of Test for Bound Co-integration

Test Statistic	Value	k
F-statistic	10.40140	3
Critical Value Bounds		
Significance	I0 Bound	I1 Bound
10%	2.72	3.77
5%	3.23	4.35
2.5%	3.69	4.89
1%	4.29	5.61

Source: Computed by the Author

Following the establishment of co-integration, the Error Correction Model (ECM) was estimated to capture both the short-run dynamics and the long-run equilibrium adjustments. The results, reported in Table 4, show that the estimated error correction term (CointEq(-1)) has the expected negative sign and is significant at the 5% level. This indicates a feedback adjustment mechanism, where deviations from the long-run equilibrium are corrected over time. The coefficient of the ECM (-0.320432) suggests that approximately 32% of the disequilibrium errors from the previous year are corrected in the current year. The coefficient for the first lag of the change in agricultural output (D(LAGRIC(-1))) is positive but not statistically significant (0.012666, p = 0.9543) as shown in Table 4. Similarly, the second and third lags of the change in agricultural output (D(LAGRIC(-2)) and D(LAGRIC(-3))) have negative coefficients, but these are also not statistically significant as seen in Table 4, indicating that past values of agricultural output have a limited long-term effect on current output levels.

In contrast, the change in carbon dioxide (D(LCO_2)) has a positive and statistically significant coefficient (1.229733, p = 0.0130) as presented in Table 4. This finding suggests that, in the short run, an increase in CO_2 emissions is associated with an increase in agricultural output. While this result appears counterintuitive, it may reflect complex short-term interactions that warrant further investigation, such as the possible effects of increased CO_2 levels on certain crop yields under specific conditions. The change in methane (D(LCH_4)) exhibits a negative and statistically significant coefficient (-2.842934, p = 0.0020) as seen in Table 4. This indicates that an increase in methane emissions is associated with a decrease in agricultural output in the short run. Lagged changes in methane (D(LCH_4(-1)), D(LCH_4(-2)), D(LCH_4(-3))) and changes in nitrous oxide (D(LN_2O), D(LN_2O(-1)), D(LN_2O(-2))) are not statistically significant (See Table 4). This suggests that these variables do not have a substantial immediate effect on agricultural output when considered with a lag. However, the third lag of the change in nitrous oxide (D(LN_2O(-3))) is statistically significant and has a negative coefficient (-3.824352, p = 0.0098). This indicates a delayed adverse effect of nitrous oxide emissions on agricultural output, which could be due to the long-term environmental impacts of excessive nitrogen use, such as soil degradation and water pollution.

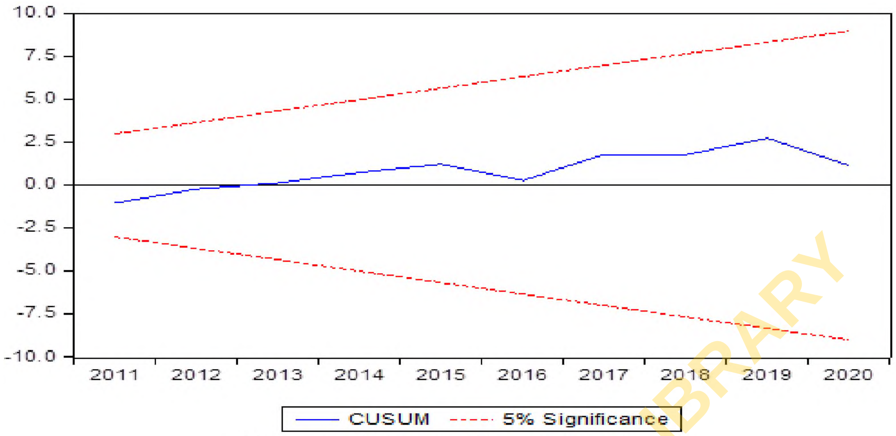
Table 4: Estimated Equations for ECM

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(LAGRIC(-1))	0.012666	0.215348	0.058818	0.9543
D(LAGRIC(-2))	-0.269888	0.195625	-1.379621	0.1978
D(LAGRIC(-3))	-0.203137	0.160963	-1.262012	0.2356
D(LCO$_2$)	1.229733	0.407703	3.016250	0.0130
D(LCH$_4$)	-2.842934	0.688229	-4.130797	0.0020
D(LCH$_4$(-1))	0.331271	1.403291	0.236067	0.8181
D(LCH$_4$(-2))	1.442360	1.361998	1.059004	0.3145
D(LCH$_4$(-3))	0.819662	0.828214	0.989673	0.3457
D(LN$_2$O)	-1.511960	1.099162	-1.375556	0.1990
D(LN$_2$O(-1))	0.064211	1.110425	0.057825	0.9550
D(LN$_2$O(-2))	-0.176678	1.024220	-0.172500	0.8665
D(LN$_2$O(-3))	-3.824352	1.201461	-3.183086	0.0098
CointEq(-1)	-0.320432	0.078060	-4.104968	0.0021

Source: Computed by the Author

The CUSUM test, a widely used diagnostic tool, assesses the stability of regression coefficients over time. The test plots the cumulative sum of the recursive residuals against time, and the results are compared against critical bounds. If the CUSUM plot stays within these bounds, it indicates that the parameters are stable over the sample period. In this study, the CUSUM plot (Figure 3) does not cross any of the 5% critical lines, indicating parameter stability. This suggests that the relationship between agricultural output and the CFP variables (CO_2, CH_4, and N_2O) remains consistent over the period studied. Stable parameters imply that the model is robust and reliable for making inferences and policy recommendations based on the estimated coefficients. This stability is critical, especially in dynamic models like the ECM, where parameter instability could lead to incorrect conclusions about the long-term and short-term relationships among the variables. The results of the CUSUM test provide confidence in the ability of ECM to accurately capture the dynamics of the relationship between carbon footprint and agricultural output, ensuring that the estimated coefficients are not affected by structural breaks or significant parameter changes over time.

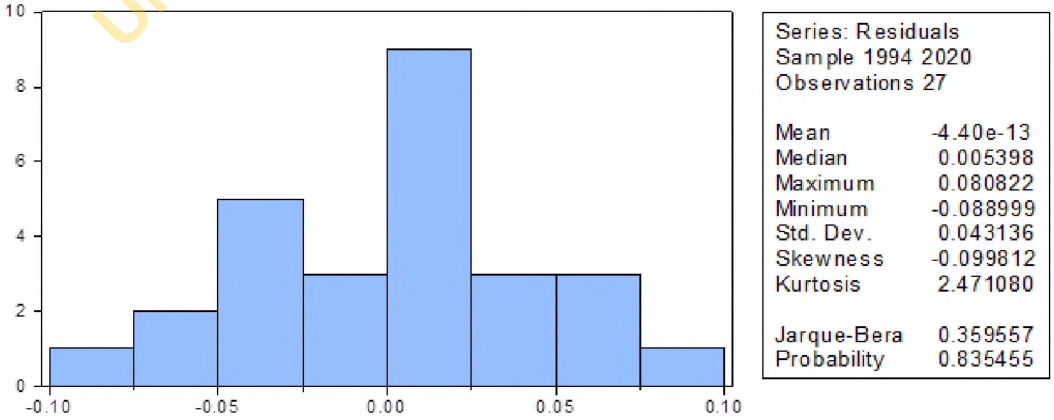
Figure 3: CUSUM Test for Stability



Source: Computed by the Author

The normality test also assessed whether the residuals of the regression model follow a normal distribution, which is a key assumption for the validity of many statistical tests and confidence intervals. The results of the normality test are presented in Figure 4. The plot indicates that the residuals are normally distributed, which is crucial for the reliability of hypothesis testing and the validity of the model's inferences. Normal distribution of residuals implies that the model's errors are random and not systematically biased, enhancing the credibility of the estimated relationships. Passing the normality test means that the model's residuals conform to the assumption of normality, ensuring that the statistical tests applied to the coefficients are valid and that the standard errors are accurately estimated. This, in turn, ensures that the confidence intervals and significance tests for the coefficients are reliable.

Figure 4: Test for Normality



Source: Computed by Author

7. Discussion of Results

The RLS regression results indicate that CO_2 emissions have a significant negative impact on agricultural output. This finding is consistent with the work of Amaefule *et al.* (2023), which found that CO_2 emissions negatively affect agricultural productivity in Nigeria. The detrimental effect of CO_2 emissions on food production can be attributed to the adverse effects of increased atmospheric CO_2 on crop yields, such as higher temperatures, altered precipitation patterns, and more frequent extreme weather events, all of which undermine agricultural productivity (Lesk *et al.*, 2022; Vijai *et al.*, 2023). The short-run dynamics from the ECM reveal a counterintuitive positive impact of CO_2 emissions on agricultural output. This result may reflect complex short-term interactions, such as the fertilization effect of CO_2 on certain crops under specific conditions, which can temporarily boost yields (Zhu *et al.*, 2023).

Methane emissions were found to have a significant negative impact on agricultural output in both the RLS regression and the ECM. This aligns with the findings of Opeyemi *et al.* (2022), which also reported a negative relationship between methane emissions and cereal yield in Nigeria. Methane, as a potent GHG, exacerbates climate change, leading to more severe and frequent adverse weather conditions that negatively affect agricultural productivity (Bibi & Rahman, 2023). The negative relationship between methane emissions and agricultural output underscores the need for effective mitigation strategies to reduce methane emissions from agricultural activities, particularly livestock production and rice paddies, which are major sources of methane (Sundar *et al.*, 2021; Nikolaisen *et al.*, 2023).

The study found that nitrous oxide emissions have a positive impact on agricultural output. This positive relationship can be attributed to the use of nitrogen-based fertilizers, which contain nitrous oxide, in enhancing soil fertility and boosting crop yields. This finding is supported by the work of Mro´wczyńska-Kamińska *et al.* (2021), who noted the critical role of nitrogen fertilizers in improving crop productivity. However, the positive impact of N_2O must be viewed with caution. While N_2O can enhance agricultural productivity, its overuse can lead to environmental degradation, including soil acidification, water pollution through runoff, and increased GHG emissions (Kollar, 2023). The ECM results also reveal a delayed adverse effect of nitrous oxide emissions, suggesting that excessive nitrogen use can have long-term negative impacts on agricultural sustainability.

The presence of a significant error correction term in the ECM indicates a strong feedback mechanism, where deviations from long-run equilibrium are corrected over time. These findings align with the EKC theory, which posits that environmental degradation initially increases with economic growth, but eventually decreases as economies mature and adopt cleaner technologies. The significant negative impact of CO_2 and methane emissions on agricultural productivity in

Nigeria suggests that the country is in the early stages of the EKC, where economic activities heavily rely on resource-intensive and polluting practices.

8. Policy Implications and Conclusion

These findings have important policy implications. First, there is a clear need for policies aimed at reducing CO_2 and methane emissions to mitigate their negative impacts on agricultural productivity. This could involve promoting the use of renewable energy, improving energy efficiency, and implementing sustainable agricultural practices that reduce methane emissions from livestock and rice paddies. Second, while nitrogen-based fertilizers are beneficial for crop yields, their use must be carefully managed to prevent environmental degradation. Policies should encourage the adoption of best management practices for fertilizer application, such as precision agriculture techniques that optimize fertilizer use and minimize runoff. Third, the counterintuitive short-term positive impact of CO_2 on agricultural output suggests that some crops might temporarily benefit from elevated CO_2 levels. However, this benefit is short-lived and outweighed by the long-term negative effects. Therefore, policies should focus on long-term sustainability rather than short-term gains. Finally, the significant adjustment speed indicated by the error correction term suggests that the agricultural sector can adapt to changes in environmental conditions over time. This adaptability should be leveraged through policies that support agricultural innovation, research, and development to enhance resilience against climate change.

In conclusion, this study highlights the complex relationship between CFP components and agricultural productivity in Nigeria. The significant negative effects of CO_2 and methane emissions on agricultural output underscore the urgent need for sustainable practices and effective mitigation strategies. While nitrous oxide emissions have a positive effect due to their role in fertilizers, careful management is essential to prevent long-term environmental degradation. Policymakers must balance the immediate needs of agricultural productivity with the long-term goal of environmental sustainability to ensure a resilient and productive agricultural sector in Nigeria.

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