



Investigating The Influence of Technological Advancement, Renewable Energy, and CO₂ Emissions on Agricultural Productivity in Nigeria: Moderating Role of Institutional Efficiency

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To Cite this Article

Anas Muhd Abubakar, & *et al.* (2025). Investigating the Influence of Technological Advancement, Renewable Energy, and CO₂ Emissions on Agricultural Productivity in Nigeria: Moderating Role of Institutional Efficiency. *Indian Development Economics Review*, 1: 1, pp. 61-84.

ABSTRACT

This study investigates the influence of technological advancement, renewable energy consumption, and CO₂ emissions on agricultural productivity in Nigeria. Recognizing the pivotal role agriculture plays in Nigeria's economic development and food security, this research explores how institutional quality influences the effectiveness of technology, clean energy, and environmental factors in enhancing agricultural outcomes. Employing the Dynamic Autoregressive Distributed Lag (DARDL) model, the analysis captures both the short-run and long-run dynamics among the variables using annual time series data from 1990 to 2023. The findings reveal that technological advancement and renewable energy consumption positively impact agricultural productivity, while CO₂ emissions exert a negative influence. Importantly, institutional efficiency significantly moderates these relationships, enhancing the positive effects of renewable energy and technology while mitigating the adverse impact of CO₂ emissions. The study underscores the importance of strengthening institutional

frameworks to optimize the benefits of technological and environmental interventions in Nigeria's agricultural sector. Policy recommendations are provided to support institutional reforms and sustainable agricultural practices.

Keywords: Technological Advancement, Green Energy, CO₂ Emissions, Agricultural Productivity, Institutional Efficiency, Dynamic ARDL, Environmental Sustainability, Nigeria

JEL CODES: N57, O13, Q10, Q21

Introduction

Agriculture remains the backbone of food security, rural livelihoods, and economic development worldwide, accounting for approximately 26.1% of global employment and 4.02% of global gross domestic product (GDP) in 2024 (Food and Agriculture Organization [FAO], 2025)). Yet, the sector operates at the intersection of two critical global challenges: the need to significantly increase productivity to meet the food demands of a growing population projected to reach 9.7 billion by 2050 (UN DESA, 2022), and the urgent requirement to reduce environmental pressures, particularly greenhouse gas (GHG) emissions, to mitigate climate change. The agricultural sector is both a victim and a contributor to climate change, responsible for an estimated 16.2 billion tonnes of CO₂ equivalent in 2022, representing between 25% and 33% of global anthropogenic emissions (FAO, 2024). These emissions, mainly from land-use changes, fertilizer application, and livestock are projecting grave threats to long-term agricultural productivity, and contribute greatly to soil erosion and nutrient depletion, intensify water scarcity through altered hydrological cycles, and heighten the frequency and severity of extreme weather events, all of which compromise food security and rural livelihoods (Intergovernmental Panel on Climate Change [IPCC], 2022).

Technological advancement remains a key driver of sustainable improvements in agricultural productivity, manifested in recent innovations, such as precision agriculture, genetically improved crop varieties, remote sensing, Internet of Things (IoT)-enabled irrigation systems, and automated machinery which enable farmers to optimize input use, reduce post-harvest losses, and strengthen resilience to climate variations (FAO, 2023; Klerkx & Rose, 2023). From the empirical viewpoint, mechanization and digital agricultural tools increase total factor productivity by reducing input wastage and enhancing decision-making efficiency (World Bank, 2024). Moreover, technology-driven efficiency gains can mitigate emissions intensity in production by lowering energy and fertilizer requirements per unit of output (OECD, 2024). However, the adoption and effective utilization of these technologies depend on factors such as

affordability, technical skills, and supportive policy environments (Olaniyan *et al.*, 2023; UNCTAD, 2024). Along with technological innovation, the deployment of renewable energy in agriculture presents a pathway to enhance productivity while lowering carbon footprints. Renewable energy sources, such as solar-powered irrigation, biogas digesters, and biomass-based processing, not only reduce reliance on fossil fuels but also provide consistent, decentralized energy access for farming operations in off-grid rural areas (Kamp & Forn, 2016). Despite these benefits, the diffusion of green energy technologies in agriculture is uneven, with uptake influenced by credit access, infrastructure availability, and institutional incentives (Onifade *et al.*, 2023).

In contrast to the productivity-enhancing potential of technology and green energy, CO₂ emissions pose a significant threat to agricultural output, both through direct climate impacts and indirect ecosystem degradation. Elevated emissions exacerbate climate change, leading to altered rainfall patterns, increased pest infestations, and soil erosion (Lobell *et al.*, 2011). For instance, a 1°C rise in temperature can reduce yields of staple crops such as maize and wheat by 5%-7% in tropical and subtropical regions (Zhao *et al.*, 2017). These impacts are particularly pronounced in developing countries like Nigeria where adaptive capacity is limited. At the same time, the agricultural sector itself contributes to emissions via energy-intensive operations, deforestation, and overuse of chemical inputs, creating a feedback loop that undermines future productivity (FAO, 2024).

Institutional quality plays a critical moderating role in shaping how technological advancement, green energy adoption, and CO₂ emissions interact to influence agricultural productivity. Strong institutions, characterized by effective governance, transparent regulation, and control of corruption, facilitate technology adoption by ensuring secure property rights, enabling access to finance, and promoting research and extension services (World Bank, 2024; UNDP, 2023). They also enhance the effectiveness of environmental regulations, incentivize renewable energy investments, and coordinate climate adaptation strategies (IEA, 2024; FAO, 2023). Conversely, weak institutions lead to policy inconsistencies, misallocation of resources, and low compliance with environmental standards, thereby diminishing the gains from technological and energy innovations (Asongu *et al.*, 2023; OECD, 2025).

In Sub-Saharan Africa (SSA), where agriculture accounts for nearly half of employment and a significant share of GDP, the interplay of these factors is particularly important. Between 2000 and 2019, CO₂ emissions from agriculture in SSA rose by 65.5%, largely due to land expansion and low adoption of low-carbon technologies

(Onifade *et al.*, 2023). Nigeria, the largest economy and most populous country in Africa, exemplifies this dynamic. Agriculture contributes about 20–25% of Nigeria's GDP and employs roughly 34.3% of its workforce (World Bank, 2023). The country emitted approximately 122,750 kt of CO₂ in 2022 (International Energy Agency [IEA], 2023), with agriculture contributing significantly through deforestation, fertilizer use, and fossil-fuel-based processing. Although Nigeria's Energy Transition Plan (2022) targets 30% renewable energy in its power mix by 2030, adoption in agriculture remains limited due to infrastructural bottlenecks, high capital costs, and weak governance mechanisms (Olaniyan *et al.*, 2023). Similarly, decentralized renewable energy projects, including solar-powered irrigation pumps and mini-grids, have shown productivity and income gains at small scales but face challenges in scaling, financing, and regulatory coordination (Adewumi *et al.*, 2023). Institutional quality plays a critical moderating role: variations in governance indicators, persistent capacity gaps in extension and research agencies, and fragmented policy implementation have constrained both agricultural modernization and renewable energy adoption (World Bank, 2023). Despite the growing recognition of the need for sustainable agricultural intensification, there is limited empirical research in Nigeria that examines the joint effects of technological advancement, green energy adoption, and CO₂ emissions on agricultural productivity, while explicitly incorporating institutional quality as a moderating factor. This study addresses this gap by investigating how institutional quality shapes the impact of these three critical drivers on agricultural productivity in Nigeria, thereby providing evidence to inform integrated policy strategies for sustainable agricultural development.

2. Literature Review

2.1. Theoretical Foundations

This study is grounded in **Endogenous Growth Theory (EGT)**, originally developed by Romer (1986, 1990) and Lucas (1988), which emphasizes that long-term economic growth is driven by **internal factors**, particularly technological innovation, human capital development, and knowledge spillovers. Unlike neoclassical models, where technological progress is exogenous, EGT posits that deliberate investments in research, skills, and innovation can sustainably raise productivity and growth rates. In the agricultural context, technological advancements, such as precision farming, remote sensing, biotechnology, mechanization, and digital advisory services, are not random occurrences; they emerge from targeted policy choices, institutional arrangements, and

investment patterns. Within this framework, **green energy adoption** is conceptualized as a form of “*directed technological change*” that complements agricultural production while mitigating environmental damage. Technologies such as solar-powered irrigation systems, decentralized mini-grids, and bioenergy solutions enhance resource-use efficiency, reduce dependence on fossil fuels, and lower input costs. By integrating sustainable energy into agricultural operations, farmers can expand production capacity without proportionally increasing CO₂ emissions, thereby aligning productivity gains with environmental goals. CO₂ emissions are treated in EGT as a **negative externality**, an unintended byproduct of production processes that erodes the productive base through soil degradation, climate variability, and biodiversity loss. While traditional EGT models focus on positive spillovers from innovation, incorporating environmental economics insights highlights that certain growth paths, if unchecked, can be self-limiting. The adoption of clean technologies and renewable energy can thus be seen as a corrective innovation that shifts the growth trajectory towards sustainability.

The moderating role of **institutional quality** is anchored in the works of North (1990) and Acemoglu and Robinson (2012), which emphasize that institutions, defined as the formal and informal rules governing economic interactions, shape the incentives for innovation and investment. Effective governance, transparent regulations, strong property rights, and efficient public administration reduce uncertainty, lower transaction costs, and enhance the returns to technological adoption. In contrast, weak institutions characterized by policy inconsistency, regulatory capture, and corruption diminish the diffusion and productivity impact of new technologies. In the context of Nigeria, institutional efficiency can amplify the positive effects of technological advancement and green energy on agricultural productivity by ensuring access to finance, supporting research and extension services, and enforcing environmental standards. Conversely, institutional weaknesses may allow CO₂ emissions to undermine agricultural performance more severely.

2.2. Previous Empirical Approaches and Findings

By giving special consideration to climate change in the form of fluctuating temperature, rainfall patterns, and acute weather circumstances, empirical research by Omachi and Friday (2025) employed Autoregressive Distributed Lag model and demonstrated that between 1991 and 2023, short-term impact of climate change exhibits a detrimental effect on agricultural productivity in Nigeria, while population growth has a positive and considerable impact on agricultural output. GDP growth has no discernible short-

term impact on agricultural output. In a similar vein, He *et al.*, (2024) examined the impact of green economic growth and renewable energy on food security in Sub-Saharan Africa (SSA) for the period 2005–2022 by applying the system Generalized Method of Moments (GMM). They found that renewable energy and green economic growth have a positive significant impact on food security, while, industrialization through its emissions, contributes negatively to food security. Danjuma *et al.* (2025) asserted that different machines and frameworks applied in agricultural farming can mitigate the CO₂ emissions of the agriculture sector if renewable energy technologies (RETs) and renewable energy sources are organized with proper agrarian loads. Umeh *et al.* (2024) evaluated the effectiveness of renewable energy initiatives in reducing the Nigeria's carbon footprint and fostering environmental sustainability and discovered a progress in achieving climate change mitigation goals through increased renewable energy use.

In another study, Khalifa (2025) explored the influence of climate change and air pollution on Tunisia's agricultural sector, employing both the ARDL and NARDL models over the period 1996-2022. The findings reveal that in the short term, CO₂ emissions were associated with a reduction in agricultural productivity, while the long-term results demonstrate a substantial negative impact of environmental degradation on the crop production. The analysis further shows that water productivity, fertilizer usage, and male employment in agriculture contribute positively to long-term agricultural output. Ejedegba (2025) considered global case studies to examine the role of renewable energy sources in powering fertilizer production and minimizing its carbon footprint and nutrient recovery systems in reducing energy consumption and improving soil health. He concluded that the integration of precision agriculture technologies, which optimize fertilizer application, reduce waste, and enhance crop productivity. Nwanaju *et al.* (2025) assessed the adoption of controlled environment agriculture (CEA) in Nigeria focusing on its feasibility, benefits, environmental impact, and socio-economic implications, and discovered that While CEA technologies offer efficiency and yield improvements, their adoption faces challenges like high initial costs, technical knowledge gaps, unstable energy infrastructure, lack of localized research on resource utilization, crop profitability, and the scalability of these systems. Redouane *et al.* (2025) employed the ARDL approach in Morocco from 1990 to 2022 and their findings indicate that CO₂ emissions and renewable energy consumption have a significant negative impact on agricultural GDP, whereas, employment in the agricultural sector did not show a significant effect on agricultural GDP.

Another study conducted by Osabohien and Timothy (2024) assessed the rising electricity consumption and its potential impact on the Malaysia's food productivity for the period 1990 to 2022 by applying Fully Modified Ordinary Least Squares (FMOLS) method. They confirmed that electricity consumption and an increase in arable land do not support food production expansion in the country. Amaefule *et al.* (2023) examined the impact of climate change through the carbon emissions on agricultural productivity in Nigeria between 1960 and 2019 by employing the bound test (ARDL) method. The result showed that CO₂ emissions and energy intensity negatively impacted crop and food production in Nigeria. Godson *et al.* (2025) evaluated the effect of carbon emission and green-house gas on sustainable development in Nigeria using Johansen Co-integration test, and fully modified Ordinary least square method. The empirical result showed that carbon emission has negative and insignificant impact on sustainable development, but green-house emission has positive and significant impact on sustainable development. Edoja *et al.* (2024) examined the effects of energy consumption, agricultural commerce, and productivity on CO₂ emissions in Nigeria using quantile regression from 1960 to 2021 and the findings revealed that the impact of agricultural raw materials imports and exports and energy consumption on carbon footprints are found to be positive.

Further empirical study by Ajayi *et al.* (2022) critically reviewed Nigeria's renewable energy policy and found out that for Nigeria to sustain economic growth especially as it relates to agriculture and food security, renewable energy for power generation must be included in the nation's rural development plan. Dimnwobi *et al.* (2022) explored the link among energy poverty, environmental degradation and agricultural productivity in 35 SSA nations using generalized method of moment technique. Findings revealed that energy poverty has a significant positive influence, while ecological footprint exhibited an inverse and significant impact on agricultural productivity. Wombo *et al.* (2023) investigated the farmers' adoption of green innovative technology in agriculture for mitigating climate change in Benue state, Nigeria using descriptive statistics approach covering a sample of 182, selected using multistage sampling technique. Their results revealed that Green innovative technology in agriculture has significant influence in mitigating climate change in Benue State. Chidiebere-Mark *et al.* (2022) explores the nexus between agricultural production, renewable energy, foreign direct investment (FDI), and carbon emissions covering thirty-one African countries using panel autoregressive distributed lag model and the results show that net FDI, fertilizer consumption, livestock production significantly increased carbon emissions, both in the short run and long run, while renewable energy use significantly decreases carbon

emissions. Chandio *et al.*, 2022) examined the effect of climate change of renewable energy, institutional quality, human capital and financial development on agricultural production in ASEAN-4, namely Indonesia, Malaysia, the Philippines, and Thailand from 1990 to 2016. The results from cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model reveal that climate change negatively affects agricultural production, whereas, renewable energy, human capital, and institutional quality affect positively agricultural production.

By applying autoregressive distributed lag, fully modified ordinary least square, a dynamic ordinary least square and a canonical cointegrating regression (CCR) Aluwani (2023) estimated the effect of South Africa's renewable energy supply, CO₂ emissions and trade openness on agricultural economic growth from 1990 to 2021. The results showed that growth in the agricultural sector leads to deterioration in the environment, while international trade benefits the sector, while the scale of renewable energy use slowed down the agricultural economy. Ali (2021) analyzed effects of renewable energy consumption, CO₂ emissions, and trade openness on agriculture value-added in West African countries using Panel Vector Error Correction Model and panel Granger causality test from 1990 to 2015. Findings show a unidirectional relationship that agriculture value-added I inversely affected by CO₂ emissions, and positively affected by renewable energy use, gross fixed capital formation and trade openness. Ali *et al.* (2021) modeled the effects of income, agricultural innovation, energy utilization, and biocapacity on Carbon dioxide in Nigeria from 1981 to 2014 by applying the novel dynamic autoregressive distributed lag simulations. The results confirmed the EKC hypothesis and found that agricultural innovation and energy utilization have an escalation effect on CO₂ emissions whereas income and biocapacity have long-run emission-reduction effects. Olisah *et al.* (2025) concluded that adoption of renewable energy technologies, such as solar power, wind energy, and biogas, mitigate greenhouse gas emissions, reduce reliance on fossil fuels, and improve energy access for rural farmers. This results in enhanced irrigation systems, mechanize farming operations, and implement precision agriculture techniques, leading to increased productivity and resilience to climate change impacts.

Bello *et al.* (2021) concluded that the consequences of climate changes are more pronounced in Nigeria, due to a surge in the use fossil-based fuels as the main energy source for electricity, transportation, industrial, agricultural, and domestic purposes, resulting in air pollution and land spills which lead to the destruction of agricultural land. Babatunde *et al.* (2024) explored various GHGs emitted through agriculture-energy use, their effects on climate change, as well as several climate change adaptation mechanisms

in the SSA, and concluded that agriculture and energy use predominantly influence the anthropogenic GHG leading to global warming which results in higher temperatures and lesser rainfall. Wang *et al.* (2023) estimated the effects of renewable energy and agriculture on CO₂ emissions in 38 SSA countries covering the period 2000–2019 and the differentiated-generalized method of moments was employed. They discovered that consumption of renewable energy reduces CO₂ emissions, while agriculture increases them. Zhang *et al.* (2022) explored the linkage between aggregate energy consumption, trade liberalization, CO₂ emissions, and modern agriculture in selected ASEAN countries from 2000 to 2020, using panel FMOLS from the United Nations Development Program. From the result, the value addition of agricultural commodities helps to reduce CO₂ emissions, while energy use escalates it in the United States. Tagwi (2022) evaluated the impact of carbon dioxide emissions, renewable energy usage, and climate change on South Africa's agricultural sector from 1972 to 2021 using Auto Regressive-Distributed Lag (ARDL) test. findings indicated that climate change reduces agricultural growth and carbon emissions rises as agricultural growth increases, while the use of renewable energy insignificantly induces agricultural growth.

2.3. Gap in literature

From the reviewed empirical literature, it can be established that a number of studies have examined the relationships between technological advancement, green energy, CO₂ emissions, and agricultural productivity. To appraise this extent, various methodologies including cross-country, regional, and country-specific analysis have been employed. The shortcomings of the prior studies lie in their focus on examining either technological advancement, CO₂ emissions and agricultural productivity or energy use, CO₂ emissions and agricultural productivity, neglecting the possible role of institutional quality in moderating the influence of technological advancement, green energy, and CO₂ emissions on agricultural productivity. Similarly, many of the reviewed studies were carried out using either multinational or panel frameworks. In contrast, our current study investigates the joint effects of technological advancement, green energy, CO₂ emissions and institutional quality on agricultural productivity in Nigeria, utilizing a multivariate framework and a country specific dataset spanning from 1990 to 2023. Following Shahbaz *et al.* (2011), the application of country-specific analysis minimizes the shortcomings associated with cross-country studies by accounting for more specific institutional, structural, and policy reform and provides greater scope for discussing the implications of policies for the country under study.

3. Data and Methodology

3.1. Data and Tested Model

To empirically assess the impacts of technological innovation, renewable energy and CO₂ emissions on agricultural productivity in Nigeria, this study uses annual time series data from 1990 to 2023. To achieve this, we specify the model to be tested by taking into account the Agricultural value-added which measures the net output of the agricultural sector, expressed in constant prices, reflecting the real growth in agricultural production.

A description of the selected variables in this study and data sources is presented in Table 1.

<i>Sign</i>	<i>Variables</i>	<i>Measurements</i>	<i>Sources</i>
AGP	Agricultural Productivity	Agricultural value-added (Constant US\$) measures the net output of the agricultural sector after adding up all outputs less intermediate inputs.	WDI
TEI	Technological Innovation	Technological Innovation is expressed as a percentage of all technologies, including those that are relevant to the environment.	OECD
INSQ	Institutional Quality	Composite function for control of corruption, government effectiveness, political stability, regulatory quality, rule of law, and voice and accountability	WDI
CO ₂	Carbon Dioxide Emissions	Emissions from burning of fossil fuels and other manufacturing activities (Measured in kilo tone).	WDI
REC	Renewable energy consumption	Renewable energy consumption (% of total final energy consumption)	WDI

Source: authors' compilation from World Bank Development Indicators (<https://databank.worldbank.org/source/world-development-indicators>) and Organisation for Economic Co-operation and Development data (<https://www.oecd.org/>)

3.2. Model Specification

The study adopts the model used by Yakubu *et al.* (2024). However, unlike their study, which examined agricultural total factor productivity, total factor productivity, gross fixed capital formation, agricultural credit guarantee scheme fund, trade, and exchange rate, our research incorporates variables such as agricultural productivity, technological

innovation, green energy consumption and institutional quality. Adopting the framework of Yakubu *et al.* (2024), the modified model is specified as follows:

$$\ln AGP_t = \beta_0 + \beta_1 \ln TEI_t + \beta_2 \ln RENC_t + \beta_3 \ln CO2_t + \beta_4 \ln INSQ_t + \mu_t \quad (1)$$

Here, β_0 represents the constant, while β_1 - β_4 are the parameters coefficients to be estimated, t is the time dimension, and μ_t denotes the error term in the model.

3.2.1. Moderating Effect of Institutional quality

This study examines the moderating effect of institutional quality on agricultural productivity through technological innovation, and renewable energy consumption by adding interaction terms ($\ln TEI_t \times \ln INSQ_t$, $\ln RENC_t \times \ln INSQ_t$, and $\ln CO2_t \times \ln INSQ_t$) to the regression model. Thus, taking into account the work of Hunjra *et al.* (2020), the mathematical representation for all the constructs is presented in a single equation as follows:

$$\ln \ln AGP_{2t} = \beta_0 + \beta_1 \ln TEI_t + \beta_2 \ln RENC_t + \beta_3 \ln CO2_t + \beta_4 (\ln TEI_t \times \ln INSQ_t) + \beta_5 (\ln RENC_t \times \ln INSQ_t) + \beta_6 (\ln CO2_t \times \ln INSQ_t) + \mu_t \quad (2)$$

3.2. Estimation procedure

Augmented Dickey-Fuller (ADF) and Phillips Perron (PP) unit-root tests were applied to assess the stationarity status of the employed data. This study further employed the innovative Dynamic Autoregressive Distribution Lag (D-ARDL) Model. This model is particularly well-suited for analyzing time-series relationships like those between technological advancement, green energy, CO₂ emissions, and agricultural productivity in Nigeria. For instance, Hassan *et al.* (2025) employed Dynamic ARDL to examine the nexus among agriculture, renewable energy, and economic growth in Somalia; this study successfully modeled both short- and long-run effects without pre-testing for variable stationarity across mixed integration orders. The model's strength with **small sample sizes** was affirmed in research by Abdu-Kadir *et al.* (2024) in Somali contexts, who highlighted DARDL's superior estimation properties in datasets with limited observations. Together, these studies validate DARDL's capacity to model complex short-run versus long-run dynamics, handle mixed integration orders, accommodate small samples, and unravel asymmetric policy impacts, making it a methodologically robust choice for our Nigeria-focused analysis.

4. Results and Discussion

4.1. Summary Statistics

The detailed summary of the descriptive statistics for the variables analyzed in this study are presented in table 2

Table 2: Descriptive Statistics Test Result

<i>Variables</i>	<i>LNAGP</i>	<i>TEI</i>	<i>RENC</i>	<i>LNCO₂</i>	<i>INSQ</i>
Mean	24.96437	-0.021041	83.74545	4.659849	-0.155942
Median	25.11628	0.058892	83.95000	4.646460	0.495133
Maximum	25.50647	1.386294	88.10000	4.875058	1.839556
Minimum	24.07446	-2.079442	79.90000	4.397661	-3.285202
Std. Dev.	0.476632	0.966696	2.573256	0.138631	1.676231
Skewness	-0.707964	-0.489086	0.051934	-0.116703	-0.668540
Kurtosis	2.229210	2.466981	1.768887	2.019696	2.020568
Jarque-Bera	2.382387	1.137518	1.399226	0.930852	2.518149
Probability	0.303858	0.566228	0.496777	0.627868	0.283917

First of all, there is negative skewness in terms of all the variables except RENC. Based on the results obtained, the mean and median values are approximately the same, while the standard deviation portrays the volatility in the study variables as it is higher in RENC compared to other variables, which is connected to inconsistent policy implementation, inadequate infrastructure, and unreliable investment flows (Bala & Sani, 2024). The Jarque-Bera statistics indicates that all indicators are normally distributed.

4.2. Unit Root Test

The study employed the Augmented Dickey Fuller (ADF) unit root test to identify the order of integration of the variables under study to select appropriate methodology in order to avoid spurious regression.

Table 3: Unit Root Test Using Augmented Dickey Fuller (ADF)

<i>Variables</i>	<i>Levels</i>		<i>1st Difference</i>		<i>P-Values</i>	<i>Remarks</i>
	<i>T-Stat</i>	<i>5% Critical Val</i>	<i>T-Stat</i>	<i>5% Critical Val</i>		
lnAGP	-0.772356	-3.548490	-5.206659	-3.552973	0.0009	I(1)
TEI	-5.506018	-3.523623	-9.252100	-3.526609	0.0000	I(1)
RENC	-2.582081	-3.562882	-5.660967	-3.568379	0.0004	I(1)
lnCO ₂	-2.829859	-3.552973	-6.172351	-3.557759	0.0001	I(1)
INSQ	-3.196477	-3.595026	-2.847006	-1.954414	0.0062	I(1)

Source: Extracts from E-view 12

Table 4: Unit Root Test Using Phillips Perron (PP)

Variables	Levels		r^{st} Difference		P-Values	Remarks
	T-Stat	5% Critical Val	T-Stat	5% Critical Val		
lnAGP	-0.932946	-3.548490	-5.203755	-3.552973	0.0009	I(1)
TEI	-5.523060	-3.523623	-26.36250	-3.526609	0.0000	I(1)
RENC	-2.652573	-3.562882	-5.669007	-3.568379	0.0004	I(1)
lnCO ₂	-2.848286	-3.552973	-6.355740	-3.557759	0.0000	I(1)
INSQ	1.858146	-3.587527	-2.917978	-1.954414	0.0052	I(1)

Source: Extracts from E-view 12

The employed variables were put through ADF and PP tests to assess their stationary properties. according to the results from Table 3 and 4, the stationarity test results show that all the variables were stationary at initial difference I(1).

4.3. Bound Test for Cointegration

Co-integration test was conducted using ARDL bound test to determine whether the variables included in the model are related in the long run.

Table 5: ARDL Bound Test

Test Statistics	Value	K
F-statistics	6.771516	4
Significance	I (o)	I (I)
10%	2.2	3.09
5%	2.56	3.49
2.5%	2.88	3.87
1%	3.29	4.37

Source: Extracts from E-view 12

Table 5 presents the results of the bound test, which compares the F-statistics with the critical bound values. The value of the F-statistic is 6.771516, demonstrating that, at all significance level, the F-statistic is bigger than upper bound of the critical values. It follows that there is degree of co-integration among the study variables. As a consequence, the study estimated the short-run and longrun Dynamic Auto-Regressive Distributed Lag (D-ARDL) model.

4.4. Dynamic ARDL Model Results

Table 6 displays the estimated results of the dynamic ARDL simulation model.

Table 6: Dynamic ARDL simulation Results

<i>Variables</i>	<i>Coefficient</i>	<i>Std. error</i>	<i>t-stat</i>	<i>P- values</i>
Δ TEI	0.001	0.002	0.310	0.767
L_TEI	0.001	0.002	-0.630	0.551
Δ RENC	0.071	0.016	-4.370	0.003***
L_RENC	0.092	0.029	-3.140	0.016**
Δ lnCO ₂	-1.196	0.314	-3.800	0.007***
L_lnCO ₂	-1.255	0.545	-2.300	0.055
Δ INSQ	10.289	1.930	-5.330	0.001***
LINSQ	5.543	3.349	-1.660	0.142
C	21.017	5.561	3.780	0.007***
<i>Moderating Effect of Institutional Quality</i>				
Δ TEI*INSQ	0.002	0.002	-1.000	0.352
L_TEI*INSQ	0.010	0.002	-0.100	0.919
Δ RENC*INSQ	0.062	0.013	4.860	0.002***
L_RENC*INSQ	0.039	0.022	1.800	0.115
Δ lnCO ₂ *INSQ	1.103	0.192	5.730	0.001***
L_lnCO ₂ *INSQ	0.499	0.337	1.480	0.183
<i>ECM(-1)</i>	-0.023400	0.003120	-7.500378	0.0000***
R-squared	0.769587			
Adjusted R-squared 0.731184				
Simulations	1000			

Source: Authors' computation using Stata 17.

Note: *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

The results from the dynamic ARDL simulation model in Table 6 revealed that agricultural productivity (lnAGP) is favorably but insignificantly impacted by technological innovation (TEI) both in the shortrun, longrun. 1% change in TEI growth increase AGP by 0.001% in both time horizons. The positive but insignificant impact of technological innovation on agricultural productivity in Nigeria can be attributed to low adoption rates among smallholder farmers, infrastructural and financial barriers, and the time lag required for benefits to materialize. Although TEI has the potential to improve yields, its penetration is limited by poor rural infrastructure, inadequate extension services, and restricted access to credit (World Bank, 2023; FAO, 2022). Both RENC and INSQ are positively related to the agricultural productivity in both time horizons. 1% change in RENC and one point change in INSQ in the short run raise agricultural productivity by 0.07% and 10.3% respectively, while 1% change in RENC significantly

induces agricultural productivity by 0.09% in the longrun, INSQ insignificantly raises it by 5.5%. the positive short- and long-run effects of renewable energy consumption (RENC) and institutional quality (INSQ) on agricultural productivity can be explained by their roles in enhancing production efficiency and reducing operational constraints. Increased RENC supports sustainable irrigation, mechanization, and post-harvest processing, lowering dependence on costly and unreliable fossil-fuel-based energy, thereby boosting output (World Bank, 2023). Similarly, improvements in INSQ such as better governance, policy stability, and enforcement of agricultural support programs enhance resource allocation and farmers' access to markets and services (FAO, 2022). The stronger and statistically significant long-run effect of RENC suggests that sustained access to renewable energy enables structural changes in farming systems, while the insignificance of INSQ in the long run may reflect persistent governance challenges, policy discontinuity, and implementation gaps that erode the initial productivity gains (NBS, 2022). In contrast, CO₂ emissions shows a negative relationship with agricultural productivity in both timeframes. 1% change in CO₂ emissions reduces agricultural productivity by 1.2% in the shortrun, and by 1.3% in the longrun. the negative short- and long-run impact of CO₂ emissions on agricultural productivity reflects the detrimental effects of environmental degradation and climate change on crop and livestock production. Rising CO₂ emissions contribute to higher temperatures, erratic rainfall patterns, soil degradation, and increased incidence of pests and diseases, all of which lower yields (IPCC, 2022; FAO, 2022).

When institutional quality (INSQ) is introduced as a moderating variable, the interaction effects between TEI, RENC, CO₂ emissions, and agricultural productivity exhibit notable shifts. The results indicate that in both the short and long run, these interaction terms, TEI*INSQ, RENC*INSQ and CO₂*INSQ have positive impact on Agricultural productivity in Nigeria. Specifically, both in the short and long run, a 1% increase in the interaction of green technology innovation and institutional quality raises AGP by 0.002% and 0.01% respectively, suggesting that when expansion in green technology innovation is coupled with institutional efficiency, improvement in agricultural yield is the result. Similarly, RENC*INSQ increases AGP by 0.06% and 0.04% respectively, in both timeframes. Finally, the CO₂*INSQ interaction has positive short-run and longrun effect, with a 1% increase resulting in 1.1% rise in AGP in the short run, and by 0.5% in the longrun. This implies that in Nigeria, institutional efficiency significantly amplifies the productivity benefits of green technology innovation, green energy consumption, and even moderates the negative

environmental impact of CO₂ emissions. This supported by recent ARDL evidence that TEI's positive effect on agricultural productivity is stronger in governance-supported environments, where policy stability and effective extension services facilitate technological uptake (Adeyemo *et al.*, 2024). Similarly, empirical studies demonstrate that renewable energy use, especially solar-powered, boosts farm productivity, with enhanced effectiveness when institutional arrangements ensure reliability and post-installation support (Ifeoma *et al.*, 2023). On the environmental side, although rising CO₂ emissions and greenhouse gases typically harm agricultural productivity, empirical studies incorporating adaptation strategies and institutional resilience suggest these effects are mitigated when institutional quality is higher, aligning with the observed positive CO₂*INSQ interaction results (Okorie & Lin, 2022). Together, this study affirms that robust institutional frameworks in Nigeria enable green innovations and energy investments to yield meaningful agricultural productivity gains while buffering environmental risks.

4.5. D-ARDL Simulations

Figure 1 shows the variable graph of the D-ARDL.

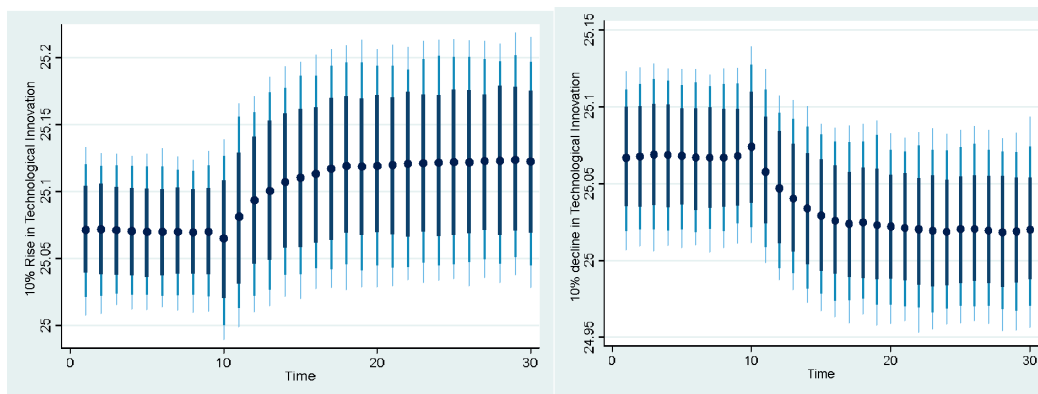


Figure 1: Representation of counterfactual shock in forecast variable (Technological Innovation)

Note: dark navy dot (·) represent the forecast shocks by 10%; navy teal, bright blue, and light-blue spikes show 75%, 90%, and 95% confidence bands.

The plots presented in Figure 1 expose that 10% of positive shocks in the estimated Technological Innovation stimulates agricultural productivity in the long run, while the same 10% negative shocks reduce it.

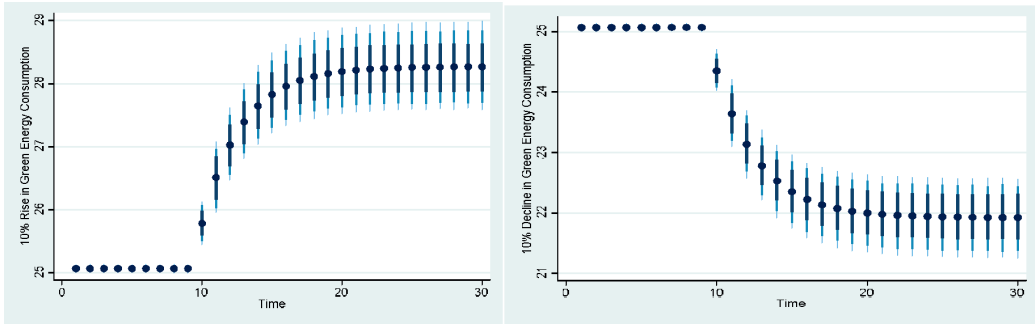


Figure 2: Representation of counterfactual shock in forecast variable (renewable energy consumption)

The impulse response plots presented in Figure 2 indicate that 10% positive shocks in the estimated renewable energy consumption promotes agricultural productivity after the first 10 years while the same 10% negative shocks in renewable energy use reduces it.

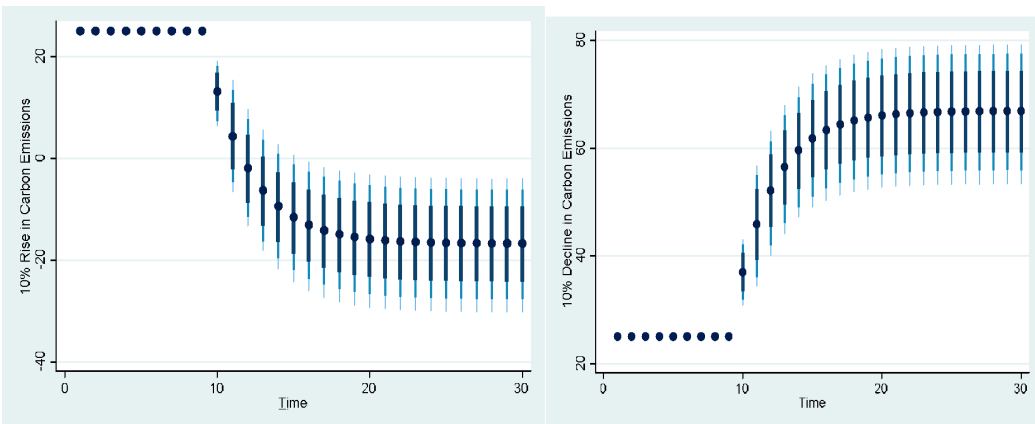


Figure 3: Representation of counterfactual shock in forecast variable (CO₂ emissions)

Figure 3 presents the impulse response plots indicating that 10% rise in CO₂ emissions negatively affects agricultural productivity in Nigeria, while the same 10% reduction promotes it.

4.9. Diagnostic Statistics Tests

The study employed many diagnostic statistical tests, and their empirical results are shown in Table 4.10, in order to confirm the consistency and reliability of the model employed in the study.

Table 7: Diagnostic statistics tests.

Diagnostic Statistics Tests	X^2 (p Values)	Results
Breusch Godfrey LM test	0.3100	No problem of serial correlations
Breusch Pagan Godfrey test	0.1398	No problem of heteroscedasticity
Ramsey RESET test	0.2196	Model is specified correctly
Jarque Bera Test	0.6564	Estimated residuals are normal

Source: Authors' Computations

Given that the model in use passed all diagnostic tests as presented in Table 7, the empirical findings imply that it is well-fitted. The Breusch Godfrey LM test demonstrates that the model is not affected by serial correlation or autocorrelation problems. The result from the Ramsey RESET test shows that the model is well specified. The Breusch Pagan Godfrey test results demonstrate the absence of heteroscedasticity in the model. Finally, the results of the Jarque Bera test demonstrates that the model's residuals are normally distributed.

Below are the model stability tests of Cusum and Cusum of Squared tests represented in graphical form. In the graphs, there is a thin blue line in-between two red bands. If the line is within the two red bands, it means the model is stable, otherwise the model is unstable. From the figures below, the lines are within the bands, suggesting that the line is within 0.05 level of significance, implying that the model has stability and that there is significant similarity in the coefficient as more observations are added to the estimated equation.

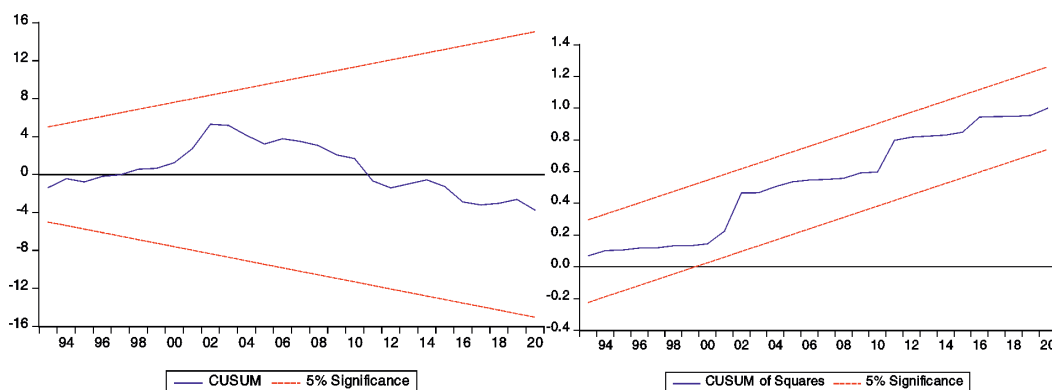


Figure 4: Cusum Test Figure 5. Cusum of Squared Test

Source: Author's computation using Eviews 10 Source: Author's computation

5. Conclusion and Policy Recommendations

This study investigated the impact of green technological innovation, renewable energy consumption and CO₂ emissions on agricultural productivity in Nigeria, while institutional efficiency was employed as a moderating factor. The empirical results from the D-ARDL analysis demonstrate that while green technological innovation exerts a positive but insignificant influence on agricultural productivity, renewable energy consumption and institutional quality significantly enhance productivity, particularly in the long run. The insignificant role of green technological innovation reflects structural bottlenecks such as weak adoption among smallholder farmers, inadequate infrastructure, (especially in rural areas), and financial constraints, while the strong effects of RENC highlight the importance of renewable energy in transforming agricultural systems in Nigeria. Moreover, CO₂ emissions undermine agricultural productivity in both the short and long run, confirming the adverse effects of environmental degradation and climate change on agriculture. However, when institutional quality is introduced as a moderating factor, the interaction effects indicate that robust institutions and policy stability stimulate the positive impacts of TEI and RENC and even mitigate the negative ecological consequences of CO₂ emissions. This underscores the central role of institutional efficiency in shaping agricultural productivity in Nigeria.

Policy Recommendations

Our findings have far-reaching policy implications aimed at maximizing agricultural productivity gains, recommending the adoption of a multi-pronged strategy anchored in renewable energy, institutional reforms, green technology adoption, and environmental sustainability in Nigeria. First, policies should give priority to expanding rural access to renewable energy, particularly solar-based irrigation and mechanization to be supported through public–private partnerships, tax incentives for domestic producers of solar equipment, and the creation of a Rural Renewable Energy Fund to provide concessional loans to agricultural cooperatives. Second, strengthening institutional quality is imperative, through reforms that enhance transparency in governance, ensure continuity in agricultural support programs, and expand extension services that facilitate technology transfer. Third, addressing the barriers hindering TEI adoption requires investments in rural infrastructure, (roads, irrigation, and storage), affordable credit access, and agricultural innovation grants. Also, capacity-building workshops and farmer field schools to be implemented in collaboration with universities and

farmer associations, can accelerate awareness and adoption. Fourth, environmental sustainability policies should focus on carbon mitigation strategies, including climate-smart agriculture, afforestation, and incentives for low-emission farming practices. Finally, integrating institutional capacity-building with green innovation and renewable energy deployment will create an enabling environment for sustainable agricultural transformation. To achieve this, a National Green Agriculture and Energy Council should be established to coordinate policies across sectors, mobilize climate finance, and monitor results. Together, these mechanisms will strengthen Nigeria's food security, enhance resilience to climate change, and ensure sustainable agricultural transformation.

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