DOES TECHNOLOGICAL PROGRESS COMPLEMENT THE IMPACT OF CARBON EMISSIONS ON POVERTY RATE? EVIDENCE FROM VECM APPROACH

AFOLABI QUADRI BALOGUN
Department of Economics, Faculty of Social Sciences, Nigerian Army University Biu, PMB1500 Biu, Borno State, Nigeria, Email: afoobalogun@gmail.com; +234 7039847090

ABSTRACT
This study examines the relationship between carbon emissions, technological advancement, and poverty reduction in Nigeria. Using a combination of Johansen cointegration and Vector Error Correction Model (VECM) techniques and 1990-2023 annual data, the study analyzes both long-run and short-run relationships among key economic and environmental variables. The findings reveal that while technological advancement significantly reduces poverty, increased carbon emissions, infrastructure expansion-measured through access to electricity-, and economic growth exacerbate poverty levels. These results underscore the importance of integrating technological innovation with environmentally sustainable policies to achieve meaningful poverty alleviation. The study recommends targeted policy interventions to enhance digital access, improve renewable energy adoption, and mitigate the adverse effects of carbon emissions on vulnerable populations. Further research should explore regional disparities and household-level impacts of technology and environmental factors on poverty.

Keywords: Carbon emissions, Technological advancement, Poverty rate, Nigeria.
JEL Classifications: O33, Q56, I32, C32, Q01

1. INTRODUCTION
Poverty remains a major global challenge, affecting billions of people, particularly in low-income and lower-middle-income countries. The World Bank (2022) defines extreme poverty as living on less than $2.15 per day, and despite global efforts to reduce poverty, progress has been uneven across regions. While some countries in East Asia and Latin America have experienced significant poverty reduction, Sub-Saharan Africa and South Asia continue to struggle with high poverty rates (Feenstra, Inklaar, & Timmer, 2015). In Africa, rapid population growth, weak economic structures, and political instability have contributed to persistent poverty (Asongu, Roux, & Biekpe, 2017).

Rapid industrialization is essential for economic growth and poverty alleviation, but has significantly increased energy consumption and carbon emissions (Biala et al., 2024), creating sustainability challenges. Developing nations, particularly in the Global South, have experienced a surge in manufacturing, infrastructure expansion, and digital technology adoption, all requiring substantial energy inputs (Zhang, Imran, & Juanatas, 2024). This growing electricity demand has led to continued reliance on fossil fuels, exacerbating greenhouse gas emissions, climate change, and air pollution (Lin & Wang, 2020). Environmental degradation and limited access to modern technology have deepened economic hardships, particularly in countries where poverty, income inequality, and weak governance hinder inclusive economic growth (Lechman & Popowska, 2022; Duong & Flaherty, 2022).

In Africa, poverty remains severe, with many people dependent on subsistence farming and informal employment. Nigeria, despite its economic strength, struggles with high poverty rates, unemployment, and income disparity (Oshota, 2019). Structural challenges, including oil dependency, inadequate infrastructure, and poor governance, have slowed progress toward sustainable economic growth (Eke, Agala, & Offum, 2019). Climate change further aggravates rural poverty by reducing agricultural productivity and increasing food insecurity (Khan & Yahong, 2021). Rising carbon emissions have also triggered climate-related disasters, such as floods and droughts, and negatively impacted public health through increased respiratory diseases and environmental degradation (Ovikuomagbe and Olusola, 2023). Addressing these challenges requires an integrated approach that combines economic, technological, and environmental strategies.

Technology plays a crucial role in poverty reduction by improving productivity, enhancing financial inclusion, and expanding access to education, healthcare, and markets (Lechman & Popowska, 2022). The expansion of mobile banking and fintech in Nigeria has provided financial access to unbanked populations, fostering small business growth. However, digital divides and income inequality persist, limiting the transformative potential of technological advancements. Furthermore, rapid industrialization and digital expansion have increased energy demand, raising concerns about sustainability (Zhang, Imran, & Juanatas, 2024). Despite these challenges, innovations in renewable energy and climate-smart technologies can promote sustainable resource use, reduce waste, enhance agricultural resilience through improved supply chains and irrigation systems, and promote sustainable economic growth (Onyechi & Ejiofor, 2021)).

Achieving sustainable development requires integrated policies that balance economic growth, technology, and climate action. Renewable energy adoption and green technologies can reduce carbon emissions while improving energy access for low-income populations (Khobai et al., 2024, Nwogwu & Ugwoke, 2024). Technology plays a key role in economic growth by creating jobs, enhancing service delivery, and generating government revenue (Solow, 1956; Felix et al., 2019; Mebawondu et al., 2012). Digital transformation, combined with sustainable energy solutions, is essential for addressing poverty and environmental challenges in Nigeria and other developing economies.

This study is motivated by the need to understand technology's role in the relationship between carbon emissions and poverty in Nigeria. While technological advancements drive economic growth and poverty reduction, they also increase energy consumption and environmental degradation (Zhang, Imran, & Juanatas, 2024). This study examines whether technological innovation mitigates poverty and reduces carbon emissions by promoting green energy solutions and improving energy efficiency (Shen et al., 2024). Key objectives include assessing the impact of technological advancement on poverty, analyzing the link between carbon emissions and economic well-being, and evaluating how GDP and infrastructure affect poverty. The paper is structured as follows: Section 2 reviews the literature, Section 3 details the methodology, Section 4 presents empirical findings, and Section 5 concludes with policy recommendations.

2. LITERATURE REVIEW

2.1 Theoretical Review

The relationship between technological advancement, carbon emissions and poverty reduction can be understood through several economic and environmental theories. These theories provide a framework for analyzing how technological progress influences economic growth, environmental sustainability, and poverty alleviation. By examining established economic models, this study aims to explore the role of technology in mitigating the negative effects of carbon emissions while promoting sustainable development and economic inclusion.

The Solow-Swan Growth Model (Solow, 1956) posits that technological progress is a key driver of long-term economic growth. In this context, technology plays a dual role. First, it enhances productivity and economic output, leading to job creation and improved living standards, thereby reducing poverty. Second, technological advancements facilitate the transition to cleaner energy sources and more efficient production processes, which, in turn, help reduce carbon emissions and promote sustainable development. This model highlights the significance of continuous investment in technology as a means of fostering both economic growth and environmental sustainability.

The Environmental Kuznets Curve (EKC) Hypothesis suggests that carbon emissions initially increase with economic growth but eventually decline as economies advance and adopt cleaner technologies (Zhao et al., 2022). This implies that in the early stages of development, industrialization and economic expansion contribute to higher emissions and environmental degradation. However, as countries progress, improved technology and environmental policies enable a shift toward greener growth. This study explores whether technological advancements help break the link between carbon emissions and poverty, leading to an environmentally sustainable growth trajectory that benefits low-income populations.

The Endogenous Growth Theory (Romer, 1990) emphasizes the role of technological progress and human capital accumulation in driving long-term economic growth. Unlike the Solow-Swan model, which treats technological progress as an external factor, this theory considers it an outcome of deliberate investment in research, education, and innovation. Investments in ICT and clean energy technology can stimulate inclusive economic growth, improve access to essential services, and create new economic opportunities, thereby reducing poverty (Lechman & Popowska, 2022). The theory underscores the importance of policies that promote knowledge diffusion and innovation to sustain economic and environmental progress.

The Energy-Poverty Nexus (Wang et al., 2024) highlights the interdependence between energy access and poverty reduction. Limited access to affordable and clean energy often traps communities in poverty by restricting their economic opportunities and reducing overall productivity. In contrast, the adoption of green technology and renewable energy sources can significantly improve living conditions by reducing reliance on polluting fuels, lowering health risks, and enhancing productivity (Albiman et al., 2015). By expanding access to modern energy solutions, technology can play a crucial role in breaking the cycle of poverty and ensuring sustainable economic development.

The relationship between technological advancement, carbon emissions, and poverty reduction is explained through key economic and environmental theories. The Solow-Swan Growth Model (Solow, 1956) highlights technology's role in boosting productivity, job creation, and clean energy adoption. The Environmental Kuznets Curve (Zhao et al., 2022) suggests emissions rise with growth but decline as economies adopt greener technologies. Endogenous Growth Theory (Romer, 1990) emphasizes innovation and knowledge diffusion in sustaining inclusive development. The Energy-Poverty Nexus (Wang et al., 2024) links clean energy access to poverty reduction. By integrating these frameworks, this study aims to examine the role of technology in achieving a balance between environmental sustainability and poverty reduction.

2.2 Empirical Review

Several studies have been carried out in the field of sustainable development, and environmental economics on the relationship among technological development, carbon emissions and poverty reduction. The relationship between carbon emissions, poverty, and sustainable development remains a crucial area of research, as economic growth often comes at the cost of environmental degradation, disproportionately affecting low-income populations. Several empirical studies provide insight into the dynamics of this relationship, highlighting the role of resource utilization, energy access, income inequality, and technological interventions in shaping carbon emissions and poverty outcomes. For clarity, the reviewed studies are grouped into three: (i) carbon emission-poverty relationship; (ii) technological progress-carbon emission relationship; and (iii) technological progress and poverty relationship.

Carbon emissions and poverty

Shaibu, Sale, and Adejoh (2024) analyze the trade-offs between charcoal production, carbon emissions, and poverty in Nigeria. Using ARDL regression on 2000–2022 data, they find that while charcoal production supports livelihoods, it accelerates deforestation and CO_2 emissions, worsening climate-related poverty. Similarly, Nabi et al. (2020) examine population growth, price levels, poverty, and emissions across 98 countries (1990–2018). Using panel cointegration and GMM, they show that lower-income groups rely on environmentally harmful practices, while high prices limit access to cleaner energy. Economic growth alone does not reduce emissions unless integrated with green technologies and environmental policies.

Okafor et al. (2024) examine the socio-economic consequences of climate change in Nigeria, highlighting its impacts on agriculture, health, and livelihoods. Using empirical analysis, the study finds that climate change exacerbates poverty, food insecurity, and economic instability. The authors recommend targeted adaptation policies, improved climate resilience strategies, and stronger government intervention. This study provides valuable insights for policymakers on mitigating climate-related socio-economic challenges in Nigeria.

Studies focusing on income inequality and environmental sustainability further reveal how disparities in wealth distribution influence carbon emissions. Khan and Yahong (2021) investigate the symmetric and asymmetric effects of poverty, income inequality, and population growth on carbon emissions in Pakistan using ARDL and NARDL co-integration models. The study analyzes data from 1980 to 2018, finding that population growth population growth contributes to rising emissions through increased energy consumption and resource exploitation. Wang, Uddin, and Gong (2021) extend this analysis globally, emphasizing that excessive natural resource exploitation significantly contributes to environmental degradation, particularly in countries with high-income inequality, where wealthier populations consume more energy-intensive goods while poorer communities rely on environmentally harmful practices. However, the study also highlights that investment in renewable energy can mitigate environmental damage.

Scholars also discovered that energy access plays a crucial role in shaping the poverty-carbon emissions nexus. Lin and Wang (2020) investigate energy poverty in China, revealing that despite significant progress in expanding electricity access, rural and low-income households still experience energy poverty due to economic disparities. Halkos and Gkampoura (2023) assess the impact of fossil fuels and renewable energy on energy poverty in Europe, finding that dependence on fossil fuels exacerbates energy poverty due to volatile energy costs, while renewable energy adoption helps alleviate energy poverty by ensuring stable and affordable electricity access. Wang, Wang, and Zhou (2024) further analyze the impact of energy poverty alleviation on carbon emissions in Belt and Road Initiative (BRI) countries, highlighting the trade-offs between expanding energy access and environmental sustainability. The study finds that reducing energy poverty initially leads to higher CO_2 emissions due to increased fossil fuel consumption, but long-term investments in renewable energy help mitigate these emissions.

Khobai, Stungwa, Oliphant, Maphuto, and Mbua (2024) investigate the symmetric impact of carbon emissions on poverty in South Africa using the Auto-Regressive Distributed Lag (ARDL) bounds test approach. The study examines data from 1985 to 2022 to determine the long-run and short-run effects of rising CO_2 emissions on poverty levels. Findings reveal that higher carbon emissions contribute to increased poverty by reducing agricultural productivity, worsening health outcomes, and increasing living costs, particularly for low-income populations. The study also highlights that environmental degradation driven by industrial pollution and fossil fuel dependency disproportionately affects vulnerable communities, limiting their economic opportunities and access to essential resources.

Whereas, macroeconomic and policy-driven approaches to addressing the carbon emission-poverty relationship underscore the need for sustainable interventions. Duong and Flaherty (2022) examine whether economic growth effectively reduces poverty, focusing on the mediating roles of carbon emissions and income inequality. Their findings indicate that while economic growth generally reduces poverty, its effectiveness is weakened when accompanied by rising carbon emissions and worsening income inequality. Zhao et al. (2022) analyze the poverty and income inequality implications of carbon pricing under long-term climate targets, finding that while carbon pricing is essential for reducing emissions, it disproportionately affects low-income households by increasing energy costs. However, redistributive policies such as revenue recycling through social transfers and green subsidies can mitigate these adverse effects, ensuring an equitable transition to a low-carbon economy.

Technology and carbon emissions

Zhang, Imran, and Juanatas (2024) analyze technological innovation, energy use, and carbon emissions in BRICS nations (1995–2023). Using GMM and panel cointegration, they find that green technologies enhance energy efficiency and lower emissions, though impacts vary by country. While economic growth initially raises emissions, sustained clean technology investment helps decouple growth from environmental harm.

Shen, Wang, Wu, and Shen (2024) analyze the relationship between the digital economy, technological progress, and carbon emissions across Chinese provinces, highlighting the dual role of digital transformation in economic growth and environmental sustainability. Using panel data from 2000 to 2023 and applying spatial econometric models and dynamic panel regression techniques, the study examines how advancements in digital technologies influence regional carbon footprints. Findings reveal that the expansion of the digital economy and technological innovation contribute to reducing carbon emissions by improving energy efficiency and optimizing industrial processes. However, in regions with high digital infrastructure growth but weak regulatory frameworks, carbon emissions initially rise due to increased energy consumption from data centers and ICT-related industries.

Lu, Xie, Liu, and Xu (2024) examine the impact of regional carbon emissions on enterprise technological innovation in China, considering the country's ongoing low-carbon transformation. Using panel data from Chinese enterprises between 2000 and 2022, the study employs econometric models, including fixed-effects and dynamic panel regressions, to assess how carbon emissions influence firms' innovation activities. The findings indicate that higher regional CO_2 emissions incentivize enterprises to invest in green technologies due to stricter environmental regulations and increasing market pressures. The study also reveals that excessive CO_2 emissions can hinder innovation by increasing operational costs and regulatory burdens, particularly for small and medium-sized enterprises (SMEs) with limited resources.

Song (2024) investigates the heterogeneous impact and regulatory effects of financial development and technological innovation on carbon emission reduction, emphasizing how different regions and economic structures influence environmental outcomes. Using panel data from 2000 to 2023 and employing dynamic panel regression and moderation analysis, the study explores how financial development—through investments, green financing, and credit availability—interacts with technological innovation to shape carbon emissions across various economic sectors. Findings indicate that financial development enhances carbon reduction efforts when paired with strong technological innovation, as it facilitates investments in clean energy and sustainable technologies. However, in regions with weak financial institutions, increased financial development can lead to higher emissions due to industrial expansion and increased energy consumption.

Asongu, Roux, and Biekpe (2017) examine the relationship between environmental degradation, information and communication technology (ICT), and inclusive development in

Sub-Saharan Africa. Using panel data from 44 countries between 2000 and 2012, they analyze how ICT penetration—measured through mobile phones, internet, and telephone lines—affects inclusive human development while considering the role of environmental factors such as CO_2 emissions. Their findings suggest that ICT expansion fosters inclusive development but also contributes to environmental degradation. However, the negative environmental effects can be mitigated through policies that promote green technologies and sustainable ICT use. The study highlights the need for a balanced approach to ICT-driven growth that prioritizes both economic inclusion and environmental sustainability.

Johnson and Keith (2004) examine the cost-effectiveness of CO_2 sequestration in fossil-fuel-based electricity generation, focusing on how natural gas prices, initial infrastructure conditions, and retrofitting options influence emission control costs. Using techno-economic modeling and scenario analysis, the study evaluates different CO_2 capture and storage (CCS) strategies for coal and natural gas power plants. Findings indicate that the cost of CO_2 sequestration is highly sensitive to natural gas prices, as lower gas prices make cleaner natural gas plants more competitive, reducing the reliance on coal. Additionally, retrofitting existing coal plants for CCS is more expensive than integrating capture technology into new plants, though site-specific factors, such as proximity to storage locations, can influence feasibility. The study suggests that policy incentives, carbon pricing, and technological advancements in CCS can enhance the economic viability of emission reductions in the electricity sector.

Technology and poverty

Lechman and Popowska (2022) provide a broad perspective on the role of digital technologies in poverty reduction across low-income and lower-middle-income countries. Using a panel dataset covering multiple nations over an extended period, they analyze how increased access to and usage of digital tools, such as mobile phones, the internet, and broadband, impact economic development and poverty alleviation. Their findings indicate that digital technologies contribute significantly to reducing poverty by enhancing financial inclusion, improving access to education and healthcare, and fostering economic opportunities. However, they also emphasize the need for supportive policies to bridge the digital divide and maximize the benefits of digital transformation for vulnerable populations.

Oshota (2019) further explores the relationship between technology access, inclusive growth, and poverty reduction in Nigeria using an error correction modeling (ECM) approach. The study finds that technology access positively influences inclusive growth by expanding financial services, creating job opportunities, and improving productivity. However, structural barriers such as inadequate infrastructure and digital literacy gaps limit the full potential of technology in reducing poverty. The study emphasizes the need for policy interventions to enhance digital access and ensure that technological advancements translate into broad-based economic benefits.

Eke, Agala, and Offum (2019) analyze the impact of technological advancement on economic growth in Nigeria, focusing on how innovations ICT, industrial automation, and digital infrastructure contribute to productivity and development. Using time-series data from 1990 to 2017, the study employs econometric techniques such as regression analysis and the Error Correction Model (ECM) to assess the short- and long-run effects of technological progress on GDP growth. Findings indicate that increased investment in technology significantly enhances economic performance by improving efficiency, fostering industrialization, and creating employment opportunities. However, challenges such as inadequate infrastructure, poor policy implementation, and digital skill gaps hinder the full benefits of technological growth.

Shotunde and Abdulazeez (2020) reinforce these findings by exploring the relationship between technology and economic growth in Nigeria from 2000 to 2019. Their study employs econometric techniques, including regression analysis and trend analysis, their findings suggest that increased adoption of technology positively correlates with economic expansion by enhancing efficiency, fostering innovation, and creating new business opportunities.

A review of these literatures revealed that technological innovation, financial development, and digital transformation play crucial roles in reducing carbon emissions while balancing economic growth across different regions and sectors. However, the effectiveness of these strategies depends on policy frameworks, regulatory strength, and access to green financing, as weak institutions can lead to increased emissions despite advancements in technology. Therefore, a comprehensive approach integrating clean energy investment, sustainable ICT expansion, and carbon mitigation policies is essential to achieving long-term environmental and economic sustainability.

This is the motivation for research to explore how technological advancements, can mitigate carbon emissions while fostering economic inclusion in Nigeria. Additionally, empirical studies employing econometric models and geospatial analysis can assess the regional disparities in technological adoption and its impact on both carbon reduction and poverty alleviation, providing insights for targeted policy interventions.

3. METHODOLOGY

3.1 Theoretical Framework

The theoretical framework adopted for the study is the Solow (1956) growth model which proposed that economic growth is the result of labour, capital and technological development. This study also incorporates the endogenous growth theory which emphasize that investments in ICT and clean energy technology can foster inclusive growth, improve livelihoods, and reduce poverty (Lechman & Popowska, 2022).

3.2 Model Specification

To empirically assess the impact of carbon emissions and technology on poverty reduction, the study adopts a time-series data regression model based on the following functional form:

$$Pov_t = \alpha_0 + \beta_1 CO2_t + \beta_2 TECH_t + \beta_3 GDP_t + \beta_4 INFRA_t + \varepsilon \quad (1)$$

Where:

Pov = Poverty rate (measured as poverty headcount ratio at $2.15 a day, % of population)
CO2 = carbon emissions per capita (metric tons)
TECH = Technology index (Total factor productivity)
GDP = Gross Domestic Product per capita (economic growth proxy)
INFRA = Infrastructure (electricity access)
εt = Error term capturing omitted variable bias and stochastic effects.

To explore whether technology mitigates the negative impact of carbon emissions on poverty, an interaction term is included:

$$Pov_t = \alpha_0 + \beta_1 CO2_t + \beta_2 TECH_t + \beta_3 (CO2 \times TECH)_t + \beta_4 GDP_t + \beta_5 INFRA_t + \varepsilon t \quad (2)$$

The interaction term $(CO2 \times TECH)_t$ tests whether technological advancement helps counteract the adverse effects of carbon emissions on poverty. In addition, α_0 represents the intercept; β_1 to β_5 are the parameters of the determinant variables to be estimated; $_t$ depicts the time series of the data, that is, 1992 – 2023 (32 years).

In addition, *Pov* is Poverty Incidence measured by the headcount index, as the dependent variable in the model, which captures deprivation in health, education, and living standards (Shaibu et al., 2024). *CO2* is carbon emissions per capita in metric tons, which contributes to climate change and environmental degradation, android disproportionately affects poor communities (Wang et al., 2021). *CO2* is expected to have a positive coefficient, implying that higher emissions increase poverty levels. *TECH* is technological advancement measured as total factor productivity index. Technological advancement could enhance economic opportunities and financial inclusion, thereby reducing poverty (Asongu et al., 2017; Lechman & Popowska, 2022). *TECH* is expected to have a negative coefficient, meaning technology adoption reduces poverty. *CO2×TECH* tests whether technology mitigates the negative effects of carbon emissions on poverty. Previous studies suggest that technology can help transition economies towards cleaner energy, reducing the environmental impact of growth (Shen et al., 2024; Lu et al., 2024). This interaction term is expected to have a negative impact on poverty, indicating that technology weakens the adverse effect of emissions on poverty, supporting the role of green innovation. *GDP* per capita, and infrastructure (INFRA), serve as control variables. Economic growth has been identified as a key determinant of poverty reduction (Feenstra et al., 2015; Duong & Flaherty, 2022), while higher GDP leads to increased income levels, and improved living conditions (Solow, 1956). Moreso, infrastructure, such as electricity access, plays a crucial role in economic development and poverty reduction (Wang et al., 2024). The two control variables are expected to have negative coefficients, implying that they ought to reduce poverty. Each variable in the model has strong theoretical and empirical backing, ensuring robustness in the analysis of carbon emissions, technology, and poverty reduction in Nigeria.

The choice of these variables is justified by economic theory and empirical evidence. The Solow-Swan growth model underscores the role of technology in driving economic development, while the Energy-Poverty Nexus highlights the role of infrastructure and clean energy in fostering economic well-being. Furthermore, all variables, except GDP, are expressed in logarithmic form to establish a log-log relationship, which helps interpret elasticities and reduces heteroskedasticity. The updated model is presented in equation (3).

$$lPov_t = \alpha_0 + \beta_1 lCO2_t + \beta_2 lTECH_t + \beta_3 (lCO2 \times lTECH)_t + \beta_4 GDP_t + \beta_5 lINFRA_t + \varepsilon t \quad (3)$$

All the data for the study, except technological development, is sourced from World Bank Poverty and Inequality Platform, and Word Development Indicators database. Total factor productivity data is derived from Our World in Data. The data for each variable was for the period 1990 – 2023.

Since time-series data often exhibit non-stationarity, the study employs the Augmented Dickey-Fuller (ADF) test to determine the order of integration of each variable. Given that variables may exhibit different integration orders (I(1) and I(2)), the Johansen cointegration test is conducted to examine whether a long-run equilibrium relationship exists among the variables. The vector error correction model (VECM) framework is adopted to capture both short-run dynamics and long-run equilibrium relationships.

4. RESULTS AND DISCUSSION OF FINDINGS

In Table 2, the descriptive statistics as well as summary for all variables in the model is presented. The table shows reveals the mean, median, maximum, minimum, standard deviation among others of all the variables in the study.

Table 1: Descriptive Statistics

	LPOV	LCO2	LTECH	LCO2_TECH	GDP	LINFRA
Mean	-0.893778	-0.387042	-0.172726	0.043529	1.578845	-0.749281
Median	-1.057966	-0.424875	-0.164029	0.048933	1.502196	-0.713558
Maximum	-0.537520	-0.093236	0.088107	0.148621	12.21039	-0.502527
Minimum	-1.175602	-0.690240	-0.474813	-0.042571	-4.597233	-1.298283
Std. Dev.	0.255655	0.159689	0.184281	0.047722	3.701237	0.186511
Skewness	0.353309	0.128620	-0.217282	0.114514	0.499591	-0.821886
Kurtosis	1.251972	1.784561	1.561002	2.192636	3.637495	3.372718
Jarque-Bera	5.036122	2.186574	3.201043	0.997745	1.990081	4.024618
Probability	0.080616	0.335113	0.201791	0.607215	0.369709	0.133680
Sum	-30.38846	-13.15944	-5.872686	1.479990	53.68074	-25.47554
Sum Sq. Dev.	2.156869	0.841521	1.120667	0.075152	452.0722	1.147947
Observations	34	34	34	34	34	34

Source: Author's computation (2025)

Table 2: Unit Root Test

Variables	t-statistic	Order of Integration	Interpretation
lPOV	-4.066276***	I(1)	Stationary at first difference.
lCO2	-6.628338***	I(1)	Stationary at first difference.
lTECH	-6.732945***	I(2)	Stationary at second difference.
lCO2_lTECH	-4.554392***	I(1)	Stationary at first difference.
GDP	-9.527131***	I(1)	Stationary at first difference.
lINFRA	-4.949687***	I(1)	Stationary at first difference.

Source: Author's computation (2025)

Table 2 shows the stationary test result of the variables which was conducted using the Augmented Dickey-Fuller (ADF) tests. The stationary test result, as shown in the table, suggests that the variables were stationary at I (1) or I (2). While *lTECH* is stationary at second difference, the remaining variables are stationary after first second differencing. This indicates that the autoregressive distribution lag (ARDL) test is appropriate for estimating the long-run relationship among the variables. Since the variables are a mix of I(1) and I(2), standard cointegration techniques like Johansen's test cannot directly handle I(2) variables. To proceed, *lTECH* would be differenced once to become I(1) before applying the Johansen cointegration test or the Vector Error Correction Model (VECM).

To proceed with the analysis, first, all variables in the model - *lPOV, lCO2,* $lCO2_t$**lTECH, GDP*, and lINFRA - are I(1), while *lTECH* is transformed to *D(lTECH)* to make it I(1). Next, is to perform the Johansen cointegration test to determine whether a long-run relationship exists among the variables. If at least one cointegrating equation is found, the Vector Error Correction Model (VECM) is estimated to examine both the short-run adjustments and the long-run equilibrium dynamics. The VECM helps to capture how deviations from the long-run equilibrium influence short-term fluctuations in the dependent variable while incorporating the speed of adjustment to restore equilibrium.

Table 3: Johansen Cointegration Test

H_i	Eigenvalue	Trace Statistic	Critical Value	Eigenvalue	Max-Eigen Statistic	Critical Value
0	0.746287	128.1415*	95.75366	0.746287	42.51806*	40.07757
1	0.706969	85.62343*	69.81889	0.706969	38.05182*	33.87687
2	0.517616	47.57161	47.85613	0.517616	22.59944	27.58434
3	0.465012	24.97217	29.79707	0.465012	19.39083	21.13162
4	0.131326	5.581344	15.49471	0.131326	4.364392	14.26460
5	0.038496	1.216951	3.841465	0.038496	1.216951	3.841465

Source: Author's computation (2025)

The Johansen cointegration test results, as presented in Table 3, indicate the presence of a long-run relationship among the variables, as both the trace and max-eigen statistics confirm at least two cointegrating equations. The trace test shows that the test statistic at rank 0 (128.1415) exceeds the critical value (95.75366), confirming at least one cointegrating relationship, while the rank 1 test statistic (85.62343) also surpasses its critical value (69.81889), suggesting a second cointegrating equation. Similarly, the max-eigen test supports this finding, with test statistics at ranks 0 (42.51806) and 1 (38.05182) exceeding their respective critical values, further validating the presence of two long-run relationships. However, at rank 2, both trace and max-eigen statistics fall below their critical values, indicating no additional cointegrating vectors beyond the second one. Given these results, a Vector Error Correction Model (VECM) is appropriate for further analysis, as it will effectively capture both the short-run dynamics and the long-run equilibrium adjustments among the variables.

$$\Delta lPOV = \alpha + \beta_1 \Delta lCO2_t + \beta_2 \Delta D(lTECH)_t + \beta_3 \Delta (lCO2 \times lTECH)_t + \beta_4 \Delta GDP_t + \beta_5 \Delta lINFRA_t + ECT(-1) + \varepsilon t \quad (4)$$

ECT(-1) represents the error correction term (speed of adjustment); while Δ represents first-differenced variables.

Table 4: VECM Long-run and Short-run.

Variables	Long-run coefficients
lCO2	1.809687***
DlTECH	-12.75218***
lCO2_lTECH	-8.151647
GDP	0.161376***
lINFRA	3.117156***
	Short-run coefficients
ΔlCO2	0.147078
ΔD(lTECH)	-1.135894
ΔlCO2_lTECH	-1.806705
ΔGDP	0.008991
ΔlINFRA	-0.150047
ECT(-1)	-0.130689***

Source: Author's computation (2025)

The Vector Error Correction Model (VECM) results reveal both long-run and short-run dynamics between the variables. In the long run, *lCO2* (carbon emissions) has a significant positive impact (1.809687***), indicating that higher emissions are associated with increased poverty. However, technological advancement (*DlTECH*) has a significant negative effect (-12.75218***), suggesting that improvements in technology contribute to poverty reduction. The interaction term (*lCO2_lTECH*) is negative (-8.151647) but not statistically significant, implying that the moderating effect of technology on emissions may not be robust. GDP positively influences poverty rate (0.161376***), while infrastructure development (*lINFRA*) also plays a significant role in elevating poverty (3.117156***). In the short run, none of the independent variables significantly affect poverty, as all short-run coefficients are statistically insignificant. However, the error correction term (-0.130689***) is negative and significant, confirming the existence of a long-run equilibrium relationship and indicating that deviations from this equilibrium correct at a speed of 13.07% per period. This suggests that while short-term effects are weak, adjustments toward long-run equilibrium occur steadily over time.

The study finds that carbon emissions significantly increase poverty in Nigeria, aligning with Khan and Yahong (2021) and Khobai et al. (2024), who highlight the adverse effects of environmental degradation on health, agriculture, and productivity. Similarly, Shaibu et al. (2024) note that carbon-intensive activities, though offering short-term economic benefits, exacerbate long-term poverty. However, technological advancement significantly reduces poverty, consistent with Asongu, Roux, and Biekpe (2017) and Lechman and Popowska (2022), who emphasize the role of digital innovations in financial inclusion and economic growth. The interaction term is negative but insignificant, suggesting that technology does not significantly mitigate the adverse effects of carbon emissions, contrasting with Shen et al. (2024) and Song (2024), who argue that innovation fosters cleaner energy solutions. The insignificant interaction term suggests technology may not effectively mitigate carbon emissions' impact on poverty, challenging assumptions about its role in promoting sustainable, inclusive economic growth. In addition, the insignificance of short-run coefficients reflects Nigeria's weak infrastructure, income inequality, and slow policy implementation, delaying the impact of technology on poverty. Unlike stronger economies, Nigeria's structural barriers hinder rapid poverty alleviation, requiring targeted policies to accelerate impact.

Unexpectedly, GDP and infrastructure (electricity access) significantly increase poverty, contradicting theories that economic growth and improved infrastructure reduce poverty (Duong & Flaherty, 2022; Lin & Wang, 2020). This suggests that Nigeria's growth is non-inclusive, benefiting only a small elite while widening income inequality (Nabi et al., 2020). Additionally, unreliable or unaffordable electricity may prevent infrastructure benefits from translating into poverty reduction (Simões & Leder, 2022). Short-run effects are statistically insignificant, implying that poverty dynamics are more evident in the long run. However, the negative and significant error correction term (ECT) confirms a stable long-run equilibrium, supporting Engle and Granger (1987) and Johansen (1991). These findings contribute to the debate on technology and environmental sustainability in poverty reduction, underscoring the need for further research on integrating clean technologies into Nigeria's development strategies.

5. CONCLUSION AND POLICY RECOMMENDATIONS

This study examines the relationship between carbon emissions, technological advancement, and poverty reduction in Nigeria from 1990 to 2023 using the Vector Error Correction Model (VECM). The results indicate that while technology significantly reduces poverty, carbon emissions worsen it. However, the positive relationship between GDP and poverty suggests that Nigeria's economic growth has been largely non-inclusive. Additionally, infrastructure, measured by electricity access, unexpectedly correlates positively with poverty, likely due to affordability issues, unreliable supply, or regional disparities, as suggested by Simões and Leder (2022).

To ensure inclusive growth, policymakers should expand affordable digital infrastructure and literacy programs, aligning with Asongu et al. (2017) and Lechman & Popowska (2022), who highlight technology's role in financial inclusion. Countries like India and Kenya have successfully leveraged digital innovations to enhance economic participation (Shaibu et al., 2024). Nigeria's non-inclusive growth, reflected in the positive GDP-poverty link, mirrors findings in resource-dependent economies (Nabi et al., 2020). Addressing income inequality through targeted social policies, as seen in Brazil and South Korea, is essential for poverty reduction (Duong & Flaherty, 2022). The positive relationship between infrastructure and poverty suggests energy access alone is insufficient without affordability and reliability (Simões & Leder, 2022). China and South Africa have improved energy accessibility through targeted reforms (Lin & Wang, 2020). Nigeria must adopt similar strategies to maximize energy's poverty-reducing potential. Finally, the poverty-exacerbating effect of carbon emissions underscores the need for green energy policies. Shen et al. (2024) and Song (2024) emphasize renewable energy's role in mitigating environmental and economic challenges. Nigeria should follow Morocco and Ethiopia's models, investing in clean energy to foster sustainable growth and long-term poverty alleviation.

To ensure effective policy implementation, key government agencies in Nigeria must take targeted actions. Specifically, the Ministry of Communications and Digital Economy should expand digital infrastructure and promote digital literacy, particularly in underserved areas. The Federal Ministry of Power & Nigerian Electricity Regulatory Commission must improve electricity affordability and reliability through subsidies and renewable energy investments. The National Environmental Standards and Regulations Enforcement Agency & Federal

Ministry of Environment should enforce carbon emission regulations and incentivize clean energy adoption. The Ministry of Finance & Central Bank of Nigeria should provide financial incentives for digital transformation and renewable energy projects. Finally, the National Bureau of Statistics & Economic Advisory Council must enhance data collection to support evidence-based policymaking for poverty reduction and environmental sustainability.
This study uses national-level data, which captures broad trends but may overlook regional disparities and micro-level variations in poverty, technology adoption, and carbon emissions. Disaggregated data, such as household or sector-specific data, could offer more precise insights into these relationships. Future research should explore renewable energy adoption's role in mitigating carbon emissions' impact on poverty and analyze regional differences in digital and energy access. Employing panel data analysis across multiple countries and spatial econometric models could further enhance understanding of how technology adoption and environmental policies influence poverty dynamics across different regions and income groups.

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