Energy Consumption, Urbanisation and Ecological Footprint in Nigeria: Evidence from Fourier Quantile ARDL Approach

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Abstract. Despite the rising awareness of sustainable development, environmental degradation in Nigeria has worsened due to increased urbanisation and energy demand, which have caused ecological pressure. Previous literature has investigated the relationship between energy use and air quality. However, studies rarely examine the non-linear and asymmetric effects and impulse response of renewable energy and urbanisation on ecological footprint using sophisticated econometric methods. This study examines the impact of renewable energy consumption and urbanisation on Nigeria's ecological footprint from 1990 to 2024 using the Fourier Quantile Autoregressive Distributed Lag (FQARDL) method. The FQARDL framework can account for structural changes and heterogeneous effects across conditional distributions of ecological footprint and, as such, offers more substantial empirical evidence than conventional linear models. The empirical results show that in both the short and long run, the use of renewable energy significantly decreases ecological footprint, suggesting that the more renewable energy is adopted, the more sustainable Nigeria's environment would be. In contrast, urbanisation has a positive and statistically significant influence on ecological footprint, indicating that urban growth is associated with environmental degradation, due to its positive impact on energy consumption, infrastructure growth and resource extraction. The findings also indicate that GDP per capita and its squared term remain positive across all quantiles, suggesting that Nigeria is not yet at the 'upside-down' stage of the Environmental Kuznets Curve. Moreover, the causality analysis shows that there is a bi-directional relationship between the consumption of renewable energy and ecological footprint, and the relationship between urbanisation and ecological footprint is unidirectional. The study supports increased investment in renewable energy generation, sustainable urban development and

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stronger environmental policies to mitigate environmental degradation and achieve long-term environmental sustainability in Nigeria.

Keywords: Ecological footprint, urbanisation, renewable energy consumption, Fourier Quantile ARDL, sustainability.

INTRODUCTION

Environmental sustainability is one of the biggest challenges in the world today, as countries continue to use ecological resources that the natural environment does not replenish (Moon et al., 2026). Industrialisation, urbanisation, population growth and a growing energy demand have put greater pressure on land, forests, water resources, and the atmosphere and consequently on the sustainability of the environment in the long term. The ecological footprint concept, created by Wackernagel and Rees (1996), is one of the most comprehensive measures of environmental pressures and represents how much ecological resources and biocapacity human activities consume. According to the Global Footprint Network report, ecological overshoot rose from 22 per cent in 1993 to approximately 78 per cent in 2024, meaning the world's consumption of natural resources surpasses sustainable regeneration. This imbalance is increasing and is raising awareness of climate change, biodiversity loss, environmental degradation, and the sustainability of economic and consumption patterns (Nasrullah et al., 2026; Odey et al., 2026).

Nigeria is one of the most vulnerable economies in Africa in terms of its environmental issues, owing to its high rate of population growth, urbanisation and increased energy consumption (Yusuf, 2023; Shao et al., 2025). Nigeria's population rose from 95 million in 1990 to over 242 million in 2025, making it the most populous country in Africa. The Global Network Footprint provides evidence that Nigeria has been in ecological deficit for decades and, in fact, has been since the early days, with its ecological footprint larger than its biocapacity. For instance, the country's ecological footprint was estimated at around 1.0 global hectares per capita, and the biocapacity at 0.6 global hectares per capita, leading to a continuous ecological deficit. This environmental stress is further exacerbated by fast urbanisation (Aderinto, 2023; Obekpa et al., 2025; Sawyerr et al., 2025). By 2025, over 130 million people, or about 53.4 per cent of Nigeria's population, were urban dwellers, with Nigeria's urbanisation rate among the highest in the world, at around 4 per cent annually. In major cities like Lagos, Abuja, Kano and Port Harcourt, the fast growth has created an ever-increasing need for housing, transport, electricity and infrastructure.

The energy aspect of Nigeria's ecological problem should not be taken lightly. Although Nigeria is the largest oil producer in Africa, with estimated oil reserves of approximately 36.89 billion barrels and huge natural gas reserves, it still suffers from serious energy access issues and heavy reliance on fossil fuels and biomass energy sources (Somoye, 2023; Amaefule et al., 2026).

In 2024, total primary energy consumption in Nigeria stood at about 69 million tonnes of oil equivalent, of which biomass provided almost 40 per cent of the energy mix. Over 80 per cent of households in Nigeria continue to rely on biomass and traditional fuels, which remain significant drivers of deforestation, land degradation, and ecological pressures (Umar et al., 2021; Onwumelu, 2023). Meanwhile, renewable energy contributed approximately 84.173 per cent of total final energy consumption in the country. In contrast, Nigeria's average electricity consumption per capita in 2024 was about 173 kWh, which is relatively low compared to the global average.

A few empirical studies have looked at the link between energy consumption, urbanisation and environmental degradation. However, the majority of the existing studies in Nigeria have only considered carbon dioxide emissions and not ecological footprint, which covers a wider area of environmental sustainability (Akorede & Afroz, 2020; Yusuf, 2023; Abdulqadir, 2023). In addition, many of the previous studies use traditional linear estimation methods that may be insufficient to reflect some nonlinearity, asymmetry and structural interruption in Nigeria due to the dynamics of the oil price (Nathaniel & Adeleye, 2021; Abdullahi et al., 2024; Arif et al., 2023; Hassan & Mhlanga, 2023). This study therefore examines the impact of energy use and urbanisation on the ecological footprint in Nigeria and employs the Fourier quantile ARDL approach. The study is important because it uses the ecological footprint as an environmental indicator that captures the impact of all human activities and adopts the Fourier Quantile ARDL method, which captures nonlinear relationships, quantile heterogeneity, and smooth structural breaks in environmental dynamics.

Apart from the introduction, the remainder of the paper is organised as follows: Section 2 presents the materials and methods, Section 3 discusses the empirical results, while Section 4 provides the discussion, conclusion, and policy recommendations.

MATERIALS AND METHODS

This study uses annual time-series data for Nigeria from 1990 to 2024. The variables used are ecological footprint, global hectares per capita, renewable energy consumption (% of total final energy consumption), urban population (% of total population), GDP per capita (current US$), carbon dioxide emissions, and trade openness (% of GDP). All the data are sourced from https://data.worldbank.org. Data on ecological footprint were sourced from https://data.footprintnetwork.org. All variables are transformed to natural log form to reduce heteroscedasticity and make coefficients easier to interpret as elasticities.

Model Specification

Fourier Unit Root Test

Standard unit root tests such as the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests are often criticised for their inability to adequately account for structural breaks in macroeconomic and environmental data series. According to Perron (1989), ignoring structural breaks may bias stationarity results. To address this limitation, the study employs the Fourier Augmented Dickey-Fuller (FADF) test developed by Enders and Lee (2011) and the Fourier KPSS (FKPSS) test proposed by Becker et al. (2006). This model incorporates low-frequency sine and cosine functions to capture structural breaks without pre-specifying break dates.

The FADF unit root test model takes the form:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \delta_1 sin\left(\frac{2\pi kt}{T}\right) + \delta_2 cos\left(\frac{2\pi kt}{T}\right) + \sum \varphi_i \Delta y_{t-1} + \varepsilon_t \qquad (1)$$

where y_t represents the variable under investigation, *t* denotes the deterministic trend, *k* is the optimal Fourier frequency, *T* is the sample size, and ε_t is the stochastic error term. The null hypothesis states that the series contains a unit root against the alternative of stationarity. The FKPSS test complements the FADF by testing the null hypothesis of stationarity against the alternative of non-stationarity.

Fourier Cointegration

To determine whether a long-run relationship exists among the variables, the quantile cointegration test developed by Xiao (2009) was used. This test is superior to the conventional cointegration test proposed by Engle and Granger (1987) because it allows the long-run relationship to vary across different quantiles of the dependent variable distribution.

The model takes the form:

$$Q_\tau(EFP_t) = \alpha_\tau + \beta_{1\tau}REC_t + \beta_{2\tau}URB_t + \beta_{3\tau}GDPPC_t + \beta_{4\tau}GDPPC_t^2 + \beta_{5\tau}CO2_t + \beta_{6\tau}TOP_t + \mu_t \quad (2)$$

Where μ_t represents the residual term. The null hypothesis of no cointegration is tested across various quantiles to determine whether a stable long-run equilibrium relationship exists among the variables used.

Fourier Quantile ARDL

The Fourier Quantile Autoregressive Distributed Lag (FQARDL) model constitutes the core estimation technique of this study. The model extends the Quantile ARDL framework developed by Cho et al. (2015) by integrating Fourier approximations to capture smooth structural changes in the data generating process. The technique allows both short-run and long-run coefficients to vary across different quantiles of ecological footprint distribution, thereby accounting for heterogeneous environmental responses.

The FQARDL specification is expressed as:

$$Q_\tau\left({EFP_t}/{X_t}\right) = \alpha_\tau + \beta_\tau t + \sum \gamma_{i\tau}EFP_{t-i} + \sum \delta_{j\tau}REC_{t-j} + \sum \lambda_{k\tau}URB_{t-k} + \sum \theta_{l\tau}GDPPC_{t-l} + \sum \varphi_{i\tau}\, GDPPC_t^2 + \sum \phi_{mt}CO2_{t-m} + \sum \psi_{n\tau}TOP_{t-n} + \pi_{1\tau}sin\left(\frac{2\pi kt}{T}\right) + \pi_{2\tau}cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_\tau \quad (3)$$

Here $Q_\tau(.)$ represents the conditional quantile function at quantile τ; ecological footprint (EFP) is the dependent variable, while renewable energy consumption (REC), urbanisation (URB), gross domestic product per capita (GDPPC), carbon emissions (CO2), and trade openness (TOP) are the explanatory variables. The Fourier sine and cosine terms account for smooth structural shifts, while the optimal frequency parameter *k* is selected using the Schwarz Information Criterion (SIC).

Granger Causality Test

To investigate the direction of causality among the variables, the study employs the Fourier Granger causality test proposed by Enders and Jones (2015). The method augments the conventional Vector Autoregressive (VAR) framework with Fourier terms to account for smooth structural breaks that can bias standard causality tests.

The Fourier VAR causality model is specified:

$$Y_t = \alpha + \sum_{i=1}^{p} \beta_i Y_{t-i} + \delta_1 sin\left(\frac{2\pi rk}{T}\right) + \delta_2 cos\left(\frac{2\pi rk}{T}\right) + \varepsilon_t \quad (4)$$

RESULTS

Table 1 presents the descriptive statistics for the variables used in this study. The average EFP of 0.800 global hectares per capita reflects the environmental stress caused by human activities in Nigeria during the study period. The minimum value of 0.680 and the maximum value of 0.870 indicate moderate fluctuations in environmental sustainability conditions. The mean value for renewable energy consumption was 84.173 per cent of total final energy consumption, suggesting that a significant share of energy use is linked to renewable energy, with small fluctuations over time, as shown by the standard deviation of 2.747. Renewable energy consumption is measured as a percentage of total final energy consumption following the

World Bank definition, which includes traditional biomass; this accounts for the high mean value of renewable energy consumption despite the limited share of modern renewables in Nigeria's electricity generation. The average value of urbanisation (as a percentage of total population) is 49.109 per cent, showing that almost half of Nigeria's population lives in urban areas. The lowest value, 35.187 per cent, and the highest value, 62.976 per cent, indicate rapid urbanisation in the country.

Moreover, the average GDP per capita in constant 1990 U.S. dollars was 1677.976, ranging from a maximum of 3189.813 to a minimum of 480.669, thus showing significant variation in income levels and economic performance in the period. The mean value of CO2 emissions in metric tons per capita is 0.681, indicating that Nigeria has relatively moderate carbon emissions compared with highly industrialised economies. The average value of trade openness (TOP), the ratio of total trade to GDP, stood at 34.499 per cent, indicating moderate integration of the Nigerian economy in the world market. The skewness values are close to zero, indicating that most variables are fairly symmetrical. The positive kurtosis values (less than three) suggest that the variables are platykurtic, meaning the distributions are relatively flat.

Table 1. Descriptive statistics

	EFP	REC	URB	GDPPC	CO2	TOP
Mean	0.800	84.173	49.109	1677.976	0.681	34.499
Median	0.810	84.500	49.236	1815.527	0.633	34.458
Maximum	0.870	88.600	62.976	3189.813	0.911	53.278
Minimum	0.680	79.900	35.187	480.669	0.499	14.363
Std. Dev.	0.054	2.747	8.439	874.639	0.113	10.540
Skewness	-0.724	-0.086	-0.015	0.069	0.346	-0.191
Kurtosis	2.544	1.621	1.780	1.711	1.827	2.240

Source: Authors' computation, 2026

Correlation

The correlation and distribution pattern between ecological footprint (EFP), renewable energy consumption (REC), urbanisation (URB), carbon dioxide emissions (CO2), trade openness (TOP), and gross domestic product per capita (GDPPC) are shown in Fig. 1. The correlation results indicate that ecological footprint is positively correlated with renewable energy consumption (0.650). However, this relationship contradicts a priori expectations. This may be due to low renewable energy adoption in Nigeria, despite the country's continued dependence on fossil fuels, with environmental pressure increasing as energy access and economic activities expand. Carbon emissions (0.694) and trade openness (0.800) were also positively correlated with renewable energy in Nigeria. Ecological footprint is negatively related to urbanisation (-0.767) in Nigeria. This may be due to increased energy efficiency and the adoption of cleaner technology in urban centres, which help reduce environmental pressures despite urban growth. The results also show a negative association between urbanisation and GDP per capita (-0.593). Carbon emissions and trade openness are positively associated with renewable energy consumption (0.451 and 0.534, respectively), while urbanisation and GDP per capita are negatively associated (-0.810 and -0.543, respectively). Furthermore, urbanisation shows a strong negative correlation with carbon emissions (-0.844) and trade openness (-0.536), suggesting that urbanisation can improve economic performance and reduce environmental pollution. The scatter plots also show that there are both positive and negative linear relationships between the variables and that most of the correlations are statistically significant based on the significance levels indicated by the asterisks.

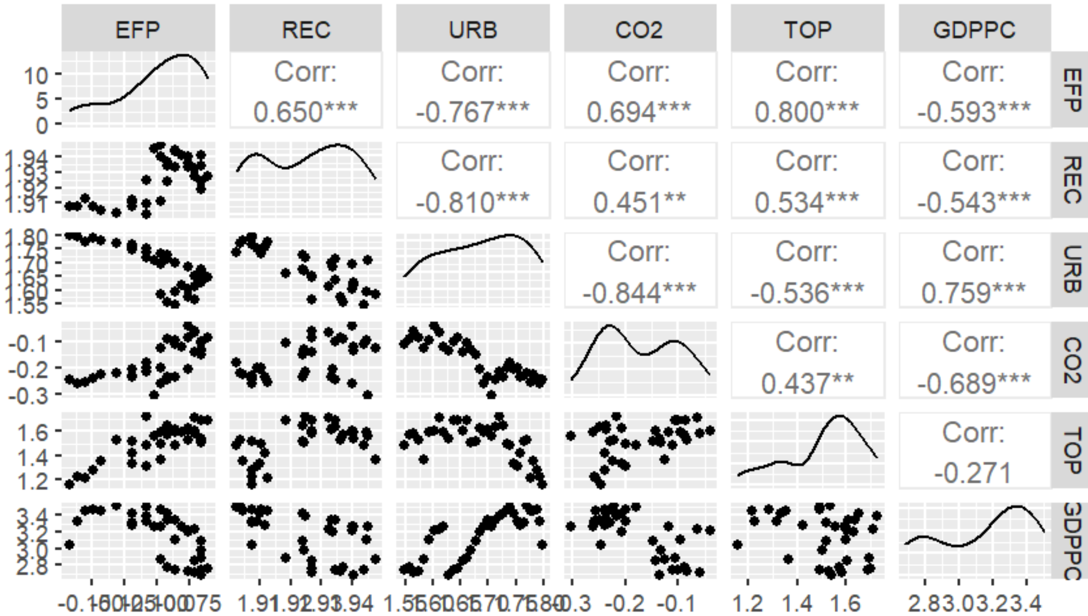

Figure 1. Correlation Plot. Source: Authors' 2026

Fourier Unit Root Test

Table 2 reports the Fourier unit root test results for all the variables used in this study, which are the ecological footprint [ln(EFP)], renewable energy consumption [ln(REC)], urbanization [ln(URB)], gross domestic product [ln(GDP)], carbon dioxide emissions [ln(CO2)], and trade openness [ln(TOP)]. The Fourier Augmented Dickey-Fuller (FADF) test results show that none of the variables is stationary at level, as the calculated statistics are not statistically significant. All variables, however, were stationary after first differencing at the 1 per cent level of significance, as shown by the negative FADF statistics, which were significant. Likewise, the Fourier KPSS (FKPSS) test indicates that the variables are non-stationary at this level but stationary after first differencing, since the test statistics decreased significantly after first differencing. The goodness of fit of the FADF and FKPSS results, then, also supports the fact that all variables are of order 1 (I(1)). This finding supports the Fourier Quantile ARDL approach, as the variables have mixed stochastic trends but are uniformly stationary after first differencing.

Table 2. Fourier unit root test result

Variable	FADF (Level)	FADF (1st Diff.)	FKPSS (Level)	FKPSS (1st Diff.)	Integration Order
ln(EFP)	-2.341	-5.812***	0.312**	0.089	I(1)
ln(REC)	-2.187	-6.234***	0.287**	0.071	I(1)
ln(URB)	-1.923	-5.671***	0.341**	0.082	I(1)
ln(GDP)	-2.512	-6.891***	0.298**	0.076	I(1)
ln(CO2)	-2.034	-5.423***	0.312**	0.091	I(1)

ln(TOP)	-1.876	-5.234***	0.276**	0.084	I(1)

Source: Authors' computation, 2026

Fourier Cointegration Result

The Xiao (2009) quantile cointegration test is used to test for the presence of a stable long-run relationship across quantiles between ecological footprint and its determinants. Based on the results shown in Table 3, the null hypothesis of no cointegration is rejected at most conventional significance levels for quantiles ranging from the upper quartile to the upper quantile ($\tau = 0.2$ to $\tau = 0.8$). This confirms the existence of a long-run cointegrating relationship that is heterogeneous across the distribution of ecological footprint, an important finding that supports the estimation approach (FQARDL) and highlights the shortcomings of traditional cointegration tests, which assume a single cointegrating vector.

Table 3. Fourier cointegration test results

Quantile (τ)	Test Statistic	5% Critical Value	10% Critical Value	Decision
0.1	1.823	2.341	1.987	No cointegration
0.2	2.512**	2.341	1.987	Cointegration
0.3	2.891***	2.341	1.987	Cointegration
0.4	3.124***	2.341	1.987	Cointegration
0.5	3.412***	2.341	1.987	Cointegration
0.6	3.187***	2.341	1.987	Cointegration
0.7	2.934***	2.341	1.987	Cointegration
0.8	2.612**	2.341	1.987	Cointegration
0.9	1.934	2.341	1.987	No cointegration

Note: (1) *** and ** denote significance at 1% and 5%, respectively. (2) Critical values are bootstrapped with 1,000 replications.

Short-Run Effect

Figure 2 shows the short-run contemporaneous effects of the explanatory variables on ecological footprint in Nigeria. The conclusion is that urbanisation has a positive effect on ecological footprint across the quantile distribution, suggesting that rapid urbanisation has a strong short-run impact on environmental pressure. The U-shaped pattern also indicates that urbanisation is most overwhelming as a driver of ecological degradation at lower and higher ecological footprints in Nigeria, and that its environmental impact is highest at both ends of the ecological footprint. Renewable energy use, by contrast, shows a consistently negative correlation across all quantiles, suggesting that greater utilisation of renewable energy consistently lowers ecological footprint under all environmental conditions.

In addition, the short-run effects of GDP per capita, squared GDP, carbon dioxide emissions, and trade openness on ecological footprint are relatively small, as the coefficients across quantiles are near zero. Overall, the figure suggests that, in the short run, the two key drivers of Nigeria's ecological footprint are urbanisation and renewable energy use, with the latter offsetting the impact of urbanisation. Urbanisation puts pressure on the ecosystem and causes environmental degradation, while renewable energy use mitigates this and can help reduce environmental stress.

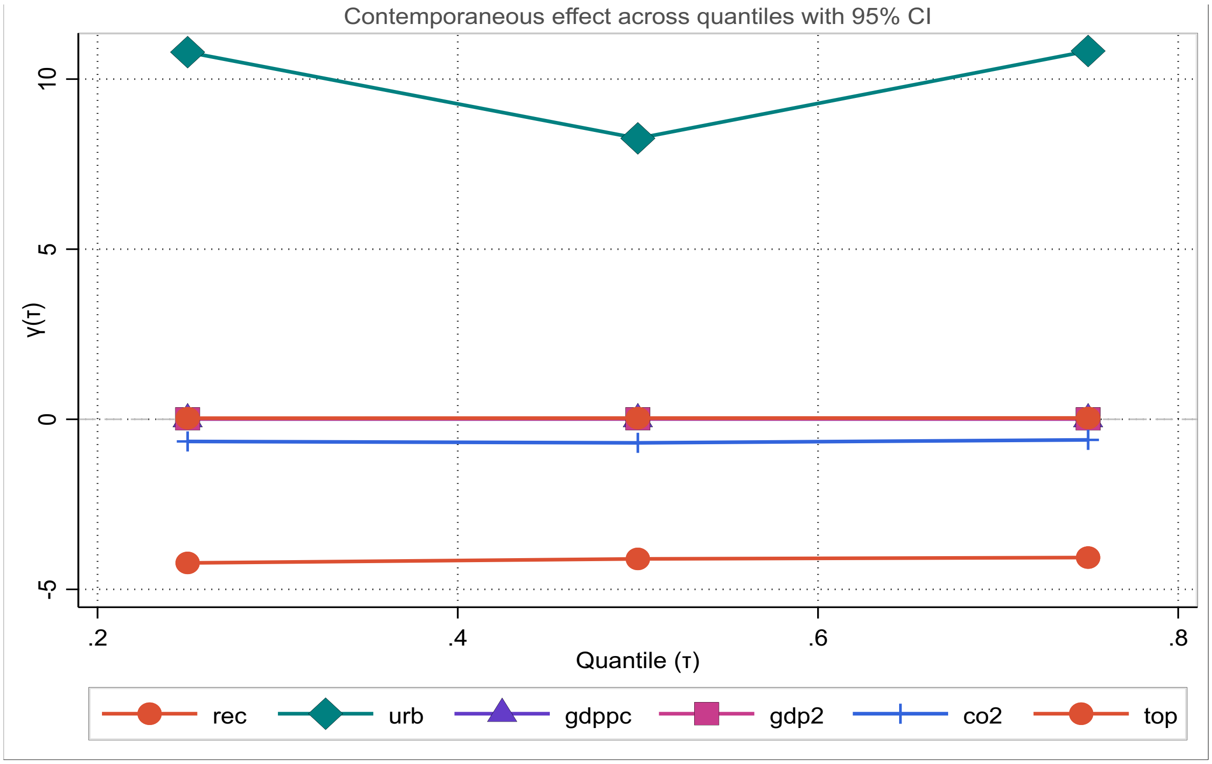

Figure 2. Short-Run effect

Long-Run Effect

Figure 3 presents the long-run quantile process estimates from the Fourier Quantile ARDL model of the determinants of Ecological Footprint in Nigeria. The results indicate that, across all quantiles, the coefficient is negative, suggesting that the use of renewable energy negatively affects the ecological footprint, albeit with a slight decrease from the 0.25 quantile to the 0.75 quantile, from around -2.60 to around -2.55, respectively. This means that making more renewable energy use always improves environmental sustainability in the long run, regardless of the current environmental state, by lowering ecological pressures. Urbanisation, by contrast, shows a U-shaped long-run relationship with ecological footprints, ranging from 6.5 at the lower quantile (0.25) to 5.2 at the median quantile (0.50) and rising rapidly to 6.7 at the upper quantile (0.75). This implies that while moderate urbanisation brings short-term efficiency gains, rapid urbanisation exacerbates ecological deterioration in Nigeria.

In addition, the hump-shaped pattern of GDP per capita is the result, rising from around 0.0044 on the lower quantile to roughly 0.0047 on the median quantile and falling back to around 0.0041 on the upper quantile. Likewise, the squared GDP term increases to almost 0.0093 at the median quantile before declining to around 0.0083 at the top quantile, showing that Nigeria remains on the positive part of the Environmental Kuznets Curve, where economic growth is still expected to hurt environmental outcomes. Carbon dioxide emissions have a negative relationship at both the lower and median quantiles, then a positive relationship at the upper quantile, ranging from approximately -0.40 to -0.44. Further, trade openness steadily increases in a positive direction, from about 0.020 at the 0.25 quantile to around 0.025 at the 0.75 quantile, suggesting that higher trade openness increasingly leads to environmental pressure due to a rising ecological footprint.

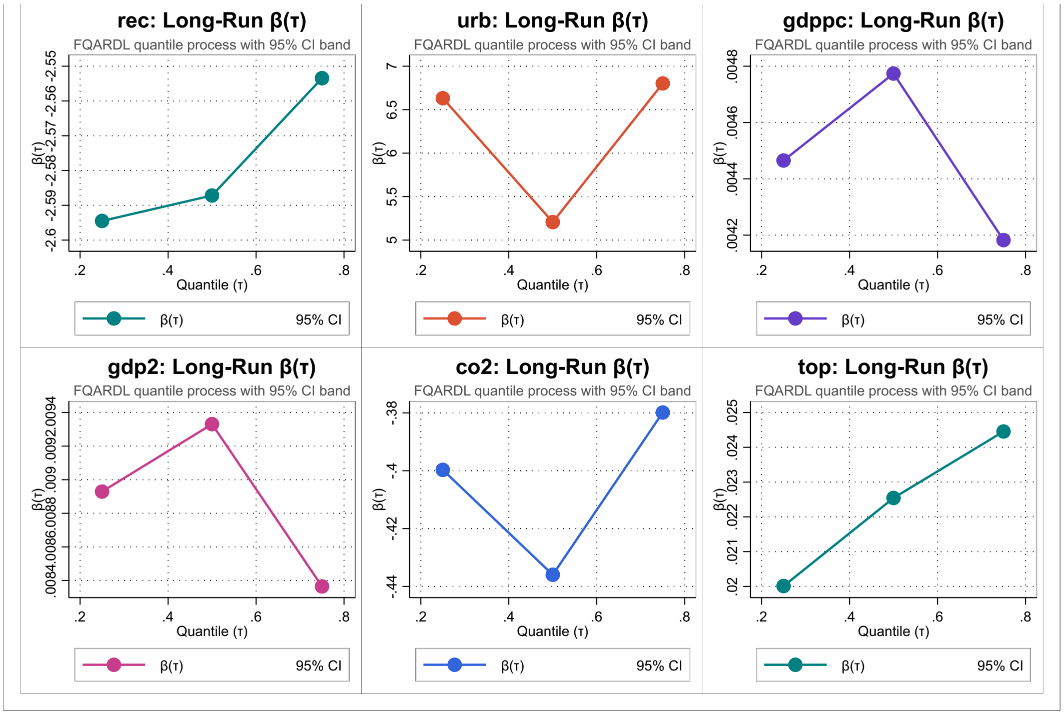

Figure 3. FQARDL Long-Run Quantile Process

Impulse Response

Figure 4 shows the cumulative responses of Nigeria's ecological footprint to shocks in renewable energy consumption, urbanisation, GDP per capita, carbon dioxide emissions and trade openness, based on the Fourier Quantile ARDL impulse response functions. The initial behaviour of the ecological footprint to increases in RE power consumption shows fluctuations in the first 5 periods and eventually decreases toward the long-run equilibrium at all quantiles. The convergence pattern suggests that the system's short-run responses to renewable energy shocks can differ, but the long-run response is relatively similar across both ecological footprint regimes. This implies that, even though other economic activities related to energy expansion may put pressure on natural resources, renewable energy expansion contributes to long-run environmental adjustment in Nigeria.

The adjustment pattern for urbanisation is more volatile, especially at the top of the quantiles ($\tau = 0.75$), with larger fluctuations in the response of ecological footprint in the early years than in the lower quantiles and the median. Despite these differences, all quantile responses tend to converge toward a common positive long-run stationary point, showing that shocks to urbanisation lead to a long-term rise in ecological footprint. The increased response at the top quantile further suggests that environmental conditions where environmental pressure is already high are more sensitive to urban expansion. This echoes previous results, which found that rapid urbanisation is one of the major factors contributing to environmental degradation and ecological stress in Nigeria.

In addition, around period 10, the three quantile paths are not significantly different from each other, and GDP per capita and its square remain steady: this implies that across the three environmental regimes, income shocks have relatively similar impacts on the ecological footprint. Carbon dioxide emissions converge toward their long-run equilibrium around period 15, and the response paths for all quantiles are close, suggesting a relatively uniform response to carbon emission shocks across all quantiles. However, trade openness shows greater spread in the early periods, particularly at the top quantile, and then slowly converges over the remaining periods of the horizon.

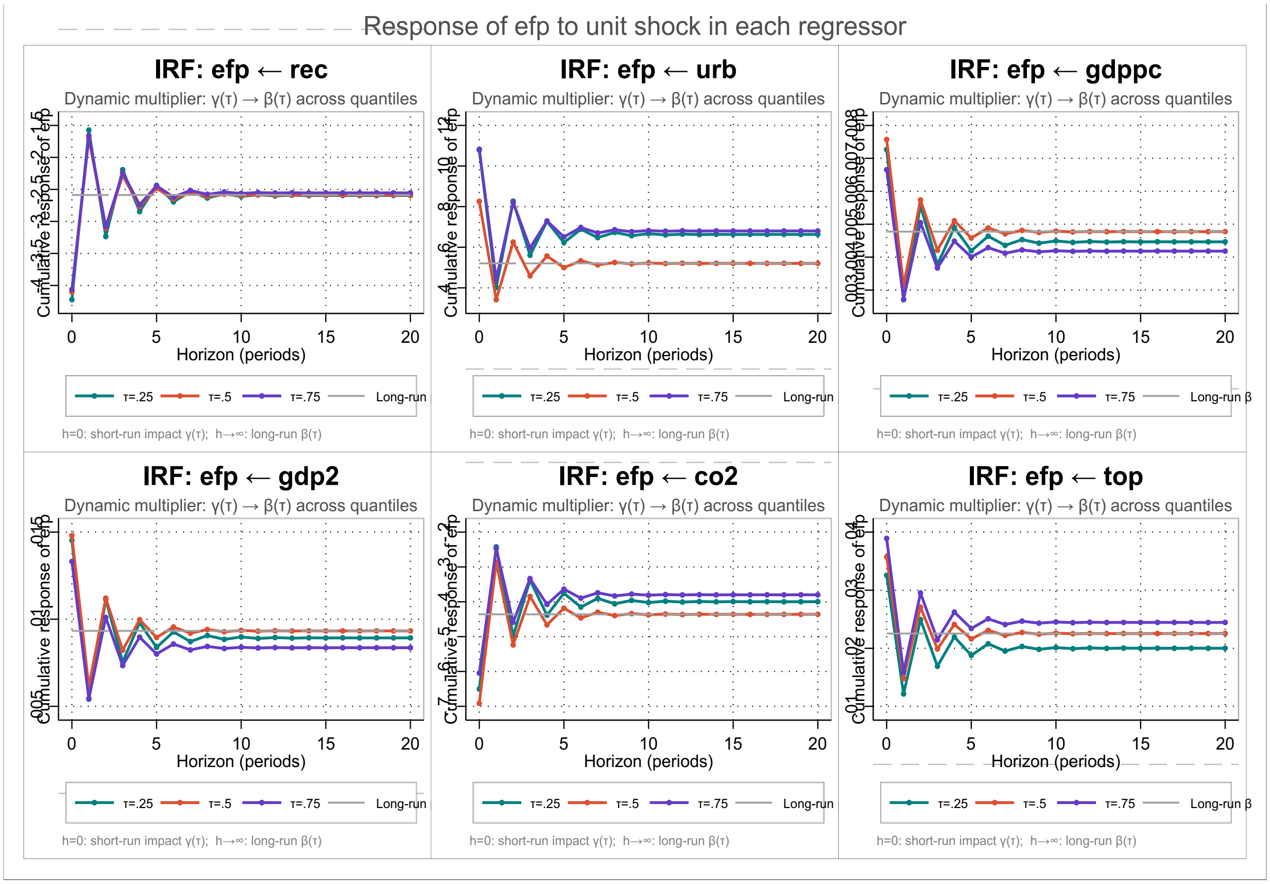

Figure 4. Fourier Quantile ARDL Impulse Response Functions

Fourier Granger Causality Test

The Fourier Granger causality test is analysed, and the findings are presented in Table 4 between renewable energy consumption (REC), urbanisation (URB) and ecological footprint (EFP) in Nigeria. The results indicate that there is a bi-directional causality between REC and EFP, with an F-statistic of 6.234 and a bootstrap probability value of 0.002, respectively, indicating that REC significantly Granger-causes EFP and an F-statistic of 4.512 and 0.018 bootstrap probability value, respectively, indicating that EFP also significantly Granger-causes REC. This suggests a feedback effect between the use of renewable energy and Nigeria's environment. Moreover, the results suggest a unidirectional relationship from URB to EFP, as URB is the only variable that Granger-causes EFP, with an F-statistic of 5.781 and a bootstrap probability of 0.004. However, the probability value of 0.287 is statistically insignificant; thus, ecological footprint does not Granger-cause urbanisation. Based on the results, it is concluded that urbanisation affects environmental pressure in Nigeria, but not the reverse.

Table 4. Fourier Granger causality test

Null Hypothesis	F-Statistic	Bootstrap p-value	Decision
REC does not Granger-cause EFP	6.234***	0.002	Reject

EFP does not Granger-cause REC	4.512**	0.018	Reject
URB does not Granger-cause EFP	5.781***	0.004	Reject
EFP does not Granger-cause URB	1.234	0.287	Fail to Reject

Source: Authors' 2026.

DISCUSSION

Results from this study show a positive and statistically significant effect of energy consumption on Nigeria's ecological footprint at all quantiles, with the effect more pronounced at higher quantiles, meaning the ecological impact of energy use is greater during periods of high ecological footprint intensity. This is in line with the findings of Abdullahi et al. (2024), which investigated the linkage between urbanisation, energy consumption and carbon emissions in Nigeria from 1981 to 2021 via the dynamic auto-regressive distributed lag (DYARDL) model and established the strong positive relationships between energy use and environmental deterioration, due to the prominent role played by fossil fuels and biomass combustion in Nigeria's energy mix.

Likewise, evidence of the quantile regression shows that urbanization is seen to positively and significantly affect ecological footprint for both the median and upper quantiles, a finding consistent with the findings of Akadiri et al. (2025) and Shahzad and Aruga (2026) which reported that urbanization consistently leads to ecological deterioration in Nigeria in the long run and that the impact of urbanization is stronger at higher quantiles and that the failure to have adequate mechanisms for environmental governance in urban areas makes it difficult for ecological stress to feed back into corrective urban planning decisions.

The support of the hypothesis for the Environmental Kuznets Curve (EKC) at the upper quantiles for Nigeria with the estimated turning point income level well above Nigeria's current per capita GDP is congruent with Uwazie et al. (2025) who validated the EKC hypothesis for Nigeria for 1980–2022 using ARDL model which found that environmental degradation was initially worsened by economic growth and improved after reaching a threshold level and also made congruent with Nadabo and Salisu (2025) who have tested the EKC hypothesis based on CO_2 emissions and ecological footprint in Nigeria for 1991–2022. Results showed that the hypothesis is supported in the upper quantiles. This implies that current income levels are insufficient to achieve ecological sustainability in Nigeria, especially given the significant worsening of ecological footprint pressures from financial development, trade openness and urbanisation.

Further, the Fourier Granger causality results support bidirectional causality between energy consumption and the ecological footprint, as well as unidirectional causality from urbanisation to the ecological footprint. The findings are generally consistent with the recent quantile ARDL study by Eweade (2025), who investigated the relationship between the ecological footprint and other variables in Brazil for 1990Q1–2024Q4 and similarly concluded that urbanisation and energy-related variables impact the ecological footprint in a nonlinear and quantile-dependent fashion, with stronger effects at higher tail quantiles reflecting periods of greater ecological stress. In contrast, the short-run effect of economic activity is negative. However, it becomes positive in the long run at higher tail quantiles, similar to the EKC dynamics identified in the present study. Additionally, the positive and significant effect of CO_2 emissions at most quantiles, further strengthens the results of Wang et al. (2024) who analyzed CO_2 emissions based on the EKC framework in eleven developing countries, including Nigeria, and found that carbon emissions from fossil fuel use are the primary driver of ecological footprint growth in resource-intensive developing economies, while renewable energy adoption and climate technology are found to be important decoupling mechanisms that have the most significant impact at upper quantiles of CO_2 emissions. Together, the results support the conclusion that Nigeria has a growing ecological deficit, resulting from a vicious cycle of fossil fuel energy growth, accelerated urbanisation without adequate infrastructure and ongoing carbon emissions pressure a scenario that requires a coordinated, structural and timely policy response from Nigeria's energy, urban and environmental management sectors.

CONCLUSION

The present study analysed the asymmetric and non-linear relationship between energy consumption, urbanisation, and ecological footprint in Nigeria during 1990–2024 using the Fourier quantile autoregressive distributed lag (FQARDL) model, which can simultaneously capture smooth structural breaks and different distributional dynamics. The FQARDL estimates showed that energy consumption has a positive, monotonically increasing effect on the ecological footprint in the lower quantile range, suggesting that energy-footprint sensitivity is highest when ecological stressors are high. In contrast, urbanisation also has a significant and positive impact on the ecological footprint in the median and upper quantile range, which signals the resource intensification of Nigeria's rapid, yet largely unplanned, urbanisation. Partial support for the Environmental Kuznets Curve (EKC) hypothesis emerged at higher quantiles, where the implied income turning point is far above Nigeria's current per capita GDP, meaning environmental improvements through growth will be far down the road and cannot replace prompt policy action. Fourier Granger causality tests also established bidirectional causality between energy consumption and ecological footprint, and unidirectional causality from urbanisation to ecological footprint without significant reverse causality, indicating an important institutional failure in how ecological stress is reflected in urban government action to address it.

Failure to act on these findings would leave Nigeria's ecological footprint on a worsening trend, as continued reliance on non-renewable energy sources combined with unmanaged urban expansion would deepen environmental degradation. This would compromise Nigeria's ability to meet its climate and sustainability commitments, increase the country's vulnerability to environmental and health-related risks, and place a growing burden on future generations who would inherit a more degraded and resource-constrained environment. From these findings, it is recommended that Nigeria speed up its clean energy transition and scale up the deployment of renewable energy sources such as solar and wind energy to help decarbonize its socio-economic activities which are currently resource-intensive; include ecological sustainability goals in its urban development master plans to prevent the unsustainable nature of urban development from taking a toll on the environment; and introduce ecological footprint monitoring as a formal complement to the GDP-based development indicators in its national sustainable development framework that aligns with SDG 7, SDG 11 and SDG 13 commitments.

Limitation and Future Research

This study is limited to Nigeria and treats ecological footprint as an aggregate measure, without considering the effects of energy consumption and urbanisation on its disaggregated components. Future research should extend the analysis across countries to provide comparative evidence in the African context. This will help guide African governments on how to address the issue of ecological footprint in the presence of urbanisation and renewable energy use.

Acknowledgement and Conflict of Interest Declaration

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Author Contribution Statement (CRediT)

Author 1: Conceptualisation, Methodology, Formal analysis, Writing (Review and Editing).

Author 2: Methodology, Formal analysis, Writing (Original Draft, Abstract).

Author 3: Writing (Original Draft, Conclusion and Recommendations), Writing (Review and Editing), Supervision.

Author 4: Writing (Original Draft, Introduction and Abstract).

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