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Advancing clean cooking transition in Nigeria through public debt and governance quality

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ABSTRACT
Access to sustainable cooking remains a major development challenge in developing economies, where traditional cooking methods still dominate. This study investigates how governance quality and public debt influence the adoption of clean cooking technologies in Nigeria from 2000Q1 to 2022Q4 using the Quantile-on-Quantile approach. Findings reveal that control of corruption, regulatory quality, rule of law, and voice and accountability consistently promote access to clean cooking, especially at higher quantiles. However, political stability and government effectiveness show limited influence at lower quantiles, reflecting persistent volatility. Public debt has minimal impact at lower quantiles, indicating that limited borrowing constrains investments in clean energy infrastructure. At higher quantiles, increased public debt supports greater government spending on sustainable energy, accelerating the clean cooking transition. The study recommends improved governance and responsible debt management to enhance clean cooking access and promote environmental sustainability in Nigeria.

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Governance; debt; clean cooking; Nigeria; affordable and clean energy

1. Introduction

Advancing access to sustainable energy is a priority in the United Nations' Sustainable Development Goals (SDGs) 7 (Adebayo, Olanrewaju, and Uzun 2025; Dimnwobi et al. 2022a; Okere et al. 2023a). This target recognises the criticality of a stable energy supply in promoting economic progress, supporting social well-being, and ensuring ecological stewardship (Dimnwobi et al. 2022b; Shobande 2020). Hence, SDG 7 represents a vital basis for achieving several other SDGs, such as healthy living (SDG 3), gender parity (SDG 5), climate action (SDG 13), and life on land (SDG 15) (Acheampong, Opoku, and Dogah 2023; Dimnwobi et al. 2023a; Tornel-Vázquez, Iglesias, and Loureiro 2024). It is surprising that although several benefits come with the utilisation of clean energy, several developing economies still find it difficult to access clean energy (Acheampong, Opoku, and Dogah 2023; Dimnwobi et al. 2023b; Okere et al. 2025; Shobande 2023). For instance, a report by the International Energy Agency (IEA) estimates that while 770 million people do not have access to electricity, 2.5 billion people do not have access to clean cooking facilities (IEA 2022). The last decade has witnessed considerable improvements in expanding households' access to electricity; however, advancements in contemporary cooking facilities have been unimpressive (Shittu, Latiff, and Baharudin 2024). For example, the average growth rate of new access to cooking fuel technologies between 2010 and 2020 is 1.0%, predominantly driven by countries in Asia (China, Pakistan, Indonesia, and India) and South America (Brazil) (ESMAP 2022; UN 2022). However, within the corresponding period, Africa had 170 million people (SEforALL 2022) who could not access clean fuels for cooking, bringing the aggregate number of people relying on traditional cooking facilities to 1 billion (IEA 2023). Because of its significant population, a large number of those without clean cooking facilities in Africa are in Nigeria. Recent statistics from the World Bank (2023) show that 26% of Nigerians have access to clean fuel,

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indicating that 74% of the nation's population relies on unsustainable cooking methods. The nation currently boasts 223 million people, and the growth rate of the population is 2.4%, indicating that Nigeria will be adding 5.37 million people annually (World Bank 2023). This shows that if no considerable efforts are made to expand access to clean cooking facilities, the number of those deprived of access could surge to approximately 4 million annually (Dimnwobi et al. 2023c). The implications of this overdependence on ecologically harmful cooking facilities are significant. For instance, available statistics show that the utilisation of conventional cooking fuels to meet domestic demands is responsible for approximately 4 million deaths as a result of indoor air pollution and has further imposed global economic losses of roughly 2.4 trillion dollars annually. Additionally, the health expenses and the cost to women utilising these eco-unfriendly cooking facilities are projected to be around $1.4 trillion and $0.8 trillion respectively (ESMAP 2020). Globally, there is a drive towards eradicating traditional cooking fuels owing to grave economic, health, and ecological implications.

In response to these negative effects of inefficient cooking fuel, improved cooking solutions have been developed to provide safer, efficient and more cleaner alternatives. These technologies are critical to the global push toward energy transitions, enhancing population health and boosting ecological quality (Shobande and Asongu 2022; Suman et al. 2025). Unlike the conventional biomass-based practices marked by inefficient stoves and open-fire setups, modern cooking options are designed to improve safety and reduce pollution. Some of the commonly utilised clean cooking solutions are electric cookers, liquefied petroleum gas (LPG) stoves, solar cookers, biogas systems and improved biomass stoves (Aladejare and Dimnwobi 2025a; Nduka 2021). These modern cooking options differs in infrastructure needs, energy source and socio-economic viability. While electric stoves and LPG are predominantly utilised in urban centres owing to efficiency and convenience, improved biogas and biomass systems provide temporary solutions in rural locations (Iglesias and Loureiro 2025). Although, solar cookers are clean and fuel-free, it is not commonly utilised owing to climate sensitivity and reduced cooking speed. To broaden this discourse, Figure 1 captures access to clean fuels and technologies for cooking, highlighting the adoption level of these modern cooking technologies. Figure 1 shows that while the global average of clean cooking solutions stands at 74%, Nigeria's access rate is considerably lower with only 26% of the nation's population having access to clean cooking solutions. This substantial imbalance reinforces the criticality of context-specific clean cooking solutions, as the drivers of access differ across regions, reinforcing the importance of country-level studies that capture locally relevant determinants often overlooked in global analyses.

Recently, decision-makers and researchers have suggested that the sluggish uptake of clean cooking facilities in Nigeria could be contingent on deficient infrastructure, steep costs, cultural hurdles, and poor awareness of the benefits of utilising these cooking methods. Although these identified variables are vital, Acheampong (2023) noted that key factors, such as investment and governance, must be prioritised because these barriers can be mitigated with increased investments and good governance. To attain universal cooking access in Nigeria by 2030, the Nigerian government relied on public borrowing to fund the

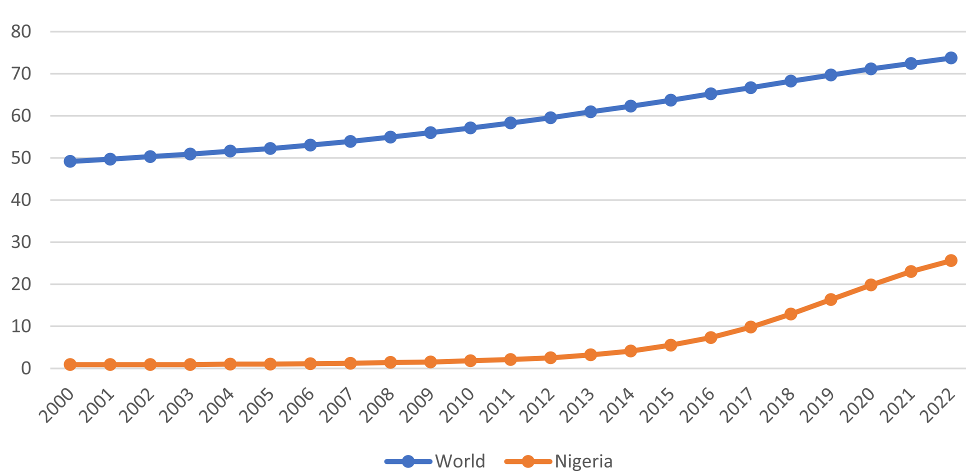


Figure 1. Access to clean fuels and technologies for cooking (% of population). Source: World Bank (2023).

requisite infrastructure. For instance, the nation's debt level skyrocketed from $48.49 billion in 2012 to $108.229 in 2023 indicating a 123% increase (DMO 2024). While the significant debt surge has raised serious concerns, the nation's decision-makers have expectedly defended borrowing decisions as necessary for the country's transition towards sustainable energy (Ezenekwe et al. 2023). Relatedly, the nation have introduced different measures to boost their governance infrastructure. While these two variables (governance and public borrowing) are important in stimulating access to clean cooking fuels and technologies, they have largely been ignored in the literature, making this study desirable.

Against this background, the research answers the following questions:

(1) Does debt stock (domestic and external debt) promote or impede clean cooking transition in Nigeria?
(2) Does governance quality stimulate or undermine Nigeria's clean cooking transition?

The foregoing research questions are vital in light of the numerous unsettled policy and empirical issues. Nigeria currently faces severe clean cooking deficit, with over 70% of the nation's households relying on environmentally unfriendly cooking options like charcoal and firewood. This reliance aggravates indoor air pollution, triggers respiratory diseases and stimulate ecological damage through carbon emissions and deforestation (Dimnwobi et al. 2021; Hammami et al. 2025; Samour et al. 2024). Although key national strategies like the energy transition plan and national clean cooking policy have been implemented, progress have been sluggish and unbalanced. One of the principal reason for this is the ineffective utilisation of public funds, including those financed by public borrowing to enhance access to energy. At the same time, increase in the nation's debt stock has not resulted into visible improvement in accelerating access to clean cooking. This disconnect prompts urgent policy concerns about the management and allocation of public debt. This issue is equally aggravated by the governance challenges in the country which further limits the efficacy of debt-funded initiatives in the sustainable energy sector. These dynamics necessitates a thorough analysis of the influence of debt and governance quality on clean cooking transition in Nigeria. However, prior studies have several notable shortcomings. First, to our research knowledge, current studies have largely investigated either the governance quality-clean cooking nexus or the correlation between debt and clean cooking in isolation, and no study have evaluated the tripartite connection between governance quality, debt and clean cooking transition within a unified framework. Second, current studies have predominantly employed national-level access to clean cooking fuels without documenting the inequalities between rural and urban populations, which are essential for region-targeted policy interventions. Third, most studies have utilised aggregate debt stock without distinguishing between foreign and domestic debt, even though these types of debt may have varying impact on clean cooking outcomes. The fourth gap is the frequent utilisation of narrow or single dimension of governance quality which do not reflect the realities of governance in an economy, particularly in developing economy. Lastly, prior studies have commonly applied linear estimation methods which are unable to document the nonlinear dynamics of the variables.

We expand the literature in multiple ways. First, this study pioneers the assessement of the combined influence of public borrowing and governance quality in driving the switch to clean cooking which has been largely ignored in the literature. Second, unlike previous studies that focused on aggregate clean cooking fuels and technologies, we disaggregated this variable into rural and urban locations. This is important, because focusing on aggregate clean cooking access masks the disparity between rural and urban access. According to statistics from the World Bank (2023), urban access to clean cooking fuels and technologies in Nigeria is 45.4% and rural access is just 10.8%. Hence, our study can be used to develop effective policies to turn this tide. Third, similar energy studies have widely utilised the public debt-to-GDP ratio or external debt as a surrogate for public borrowing. However, given the peculiarity of Nigeria's debt landscape, we use disaggregated measures. This is essential given that in 2023, the country's domestic debt constituted 60.74% of its debt stock, while external debt represented 39.26% of the nation's entire debt stock. Using these disaggregated measures will ensure that Nigerian policymakers know the debt category to prioritise for the transition to clean cooking energy. Fourth, to broaden our insight into the clean cooking transition effect of governance quality, we adopted comprehensive measures of governance. This approach differs from previous studies that have utilised the sole variable to proxy governance quality, thus propelling policy improvements and facilitating evidence-driven choices. Finally, we employ the recently introduced quantile-on-quantile regression (QQR), which facilitates the assessment of the connections between the variables across various parts of the data distribution, offering better insights than traditional approaches. This technique differs significantly from linear models because it is capable of capturing nonlinear connections between variables, which is vital in real-world contexts where linear correlations may not apply.

The remainder of the study follows this pattern. Section 2 provides insights into the relevant literature. Section 3 describes the study's data and methodology. The presentation of the outcomes is presented in Section 4, while Section 5 discusses the study with policy suggestions.

2. Insights from the literature

This section was segmented into five strands. The first section conceptualises the key variables. The second segment documents the relevant theories and the third part pertains to studies on debt-clean cooking. The fourth section focuses on the clean cooking effect of governance quality while the last section documents the empirical gaps.

2.1. Conceptual insights

Clean cooking access refers to the availability, affordability, and steady utilisation of sustainable fuels and technologies like LPG, biogas and electricity that reduce the vulnerability of households to toxic indoor pollutants (Acheampong 2023). Clean cooking access is broadly acknowledged as a vital element of public health and energy justice with direct effects on ecological preservation and gender equity, given the greater toll on women and children (Shittu, Latiff, and Baharudin 2024). In the context of our study, public borrowing denotes the financial obligations incurred by the public sector through external or domestic borrowing, primary utilised to finance national development initiatives. This comprises of bonds, loans and other debt instruments employed for infrastructure financing (Onuoha et al. 2023a; Shobande and Ogbeifun 2025). Public borrowing can be a catalyst for sustainable energy transitions when deployed and managed strategically. However, inefficient debt management could become a fiscal strain, constraining government's ability to fund vital initiatives like clean cooking or to sustain current infrastructure. Meanwhile, governance quality represents the ability of institutions to design and execute strategies, ensure accountable and transparent utilisation of public resources and maintain the rule of law (Murshed 2023). It comprises several dimensions like regulatory quality, political stability, government effectiveness among others (Okere et al. 2025a). High governance structure encourages the effective utilisation of borrowed resources, curb wastages and improves the implementation of energy policies. In contrast, poor governance can impede purpose-driven public spending, resulting to misallocation and failed projects (Aladejare and Dimnwobi 2025b)

2.2. Theoretical foundations

Keynesian theory, proposed by the renowned economist John Maynard Keynes in the 1930s, highlights that government expenditure can enhance economic advancement, even if it results in a rise in public borrowing (Nwokoye et al. 2024). Applying this to our study, this framework proposes that using public debt to fund green energy facilities can elevate economic activities and enhance clean cooking fuels (CCF) technologies (Okere et al. 2023b). Keynes presumed that expenditure of this nature may have a multiplier impact, possibly neutralizing debt's negative effects. On the other hand, in 1980, Krugman established the debt overhang theory, underlining that exorbitant debt levels can impede economic progress and investments (Onuoha et al. 2023a). Krugman's assumptions are predicated on the fact that increasing debt levels could engender instability and lessen both private and public investments, which could probably lower the resources available for sustainable cooking endeavours (Dimnwobi et al. 2023b). In the context of our research, this theory shows that nations with elevated debt burdens may be unable to fund clean energy initiatives or offer CCF inducements. These frameworks document that government borrowing substantially shapes public expenditure choices and private sector investment, although they differ in their perspectives on the possible impacts of enhanced public borrowing on development initiatives, such as CCF (Onuoha et al. 2023b).

Everett Rogers formulated the diffusion of innovation theory in his seminal work in 1962, titled 'Diffusion of Innovations.' This framework explains why, how, and at what rate novel technologies and ideas expand through culture (Katutsi et al. 2023; Okere, Dimnwobi, and Fasanya 2025b, 2025c). In the context of governance quality and CCF, this hypothesis presumes that CCF uptake is an innovation that spreads through social systems. The theory argues that robust governance can stimulate this diffusion by expanding the main variables that shape adoption, namely, trialability, compatibility, relative advantage, observability, and complexity. Good governance can increase the perceived gains in the utilisation of clean cooking (relative advantage), ensure compatibility with current needs and values, decrease complexity via support and education, offer possibilities for trialability through pilot projects, and broaden observability using demonstration initiatives and campaigns on public consciousness (Lakum and Kumar 2024). The framework also argues that various adopter groups (innovators, laggards, late majority, early adopters, and early majority) can react distinctly to governance initiatives, indicating the need for targeted strategies to strengthen the universal uptake of CCF (Takahashi, Figueiredo, and Scornavacca 2024). Institutional theory is another model that can be used to examine the influence of governance infrastructure and clean cooking. This theory benefited from Philip Selznick's works in the 1940s and the 1950s, as well as Brian Rowan, John Meyer, Walter Powell, and Paul DiMaggio's works in the 1970s and the 1980s (Kahupi et al. 2024). This framework documents that societal behaviour is influenced by the institutional environment, which involves norms, informal and formal rules, and cultural orientations. This theory states that CCF uptake is shaped by the quality of governance framework. It presumes that good governance results in better regulations, effective strategies, and enforcement methods that enhance sustainable cooking (Alam and Miah 2024). Institutional theory also assumes that robust institutions can generate legitimacy for initiatives on clean cooking, promote resource allocation, and match societal standards with green practices. Additionally, it presumes that institutional isomorphism can result in the successful spread of clean cooking strategies across diverse nations or regions with comparable institutional contexts.

2.3. Public debt and clean cooking

Public borrowing can act as a vital funding source for subsidising clean fuel technologies, broadening sustainable cooking infrastructure and encouraging initiatives that boost household uptake. When allocated strategically, debt-financed initiatives can tackle affordability impediments and expand clean cooking access to vulnerable populations. In spite of its potential, there is scarcity of studies on the implications of debt on clean cooking transition, leaving a notable gap in both public finance and energy literature. Okere et al. (2023b) represents the only study on debt-clean cooking nexus and the authros report that public borrowing is effective in stimulating CCF in Africa. The literature on public borrowing on CCF is limited. Given the paucity of studies on debt and CCF, studies on government borrowing on electrification, and green energy utilisation are included, given their interconnectedness with the wider energy transition and sustainable development agenda. For instance, Onuoha et al. (2023a) apply the Feasible Generalized Least Squares for African data between 1996 and 2020 and confirm that public borrowing aids green energy consumption. In the case of European nations, Florea et al. (2021) affirmed that public borrowing promotes clean energy utilisation, indicating the pro-clean energy effects of debt stock. The conclusions of Farooq et al. (2022) for Islamic nations are slightly different. The study finds a nonlinear connection between debt and energy poverty (poor electricity access), showing that debt is vital in reducing energy insecurity (expanding access to electricity) up to a certain level, but once this level is attained, any further debt incurred will hurt the alleviation of energy insecurity (decrease electricity access).

In contrast, some studies have found that debt is not essential for green energy utilisation. Onuoha et al. (2023b) used African data from 1990 to 2020, and a generalised method of moments (GMM) document that debt stock undermines clean energy utilisation. Auteri et al. (2024) find that the transition to sustainable energy sources is hampered by government debt in the G7 nations. Sadiq et al. (2024) found, using data from BRICS, that external borrowing hinders clean energy transition. Wang et al. (2021) concluded that expanding debt levels does not stimulate the demand for clean energy, showing that public debt does not encourage the utilisation of sustainable energy in BRICS nations. Hashemizadeh, Bui, and Kongbuamai (2021) disclosed that public debt is ineffective in encouraging the adoption of clean energy in emerging nations. In a country case study, Jabari, Aga, and Samour (2022) affirmed a negative connection between external borrowing and green energy in Turkey and suggested that the nation's decision-makers should rethink foreign debt strategies to guarantee a transition to clean energy.

2.4. Clean cooking effects of governance quality

Governance quality shapes how public resources are deployed and utilised including debt stock. Strong institutions uphold accountability, transparency and effective implementation of policy which are vital for widening clean cooking access. However, the influence of governance quality on clean cooking access is limited in the literature, particularly in the Nigerian context. Murshed (2023) established that the enhancement of institutional quality in Latin American and Caribbean countries leads to a surge in CCF accessibility. Acheampong, Opoku, and Dogah (2023) also confirmed that governance boosts the uptake of CCF in Africa from 1990 to 2017 using the Driscoll-Kraay estimator. Kwakwa (2024) reveal that governance efficiency considerably drives clean cooking transition in Africa. Considering only one dimension of governance quality (corruption), Adjei-Mantey, Kwakwa, and Ankrah (2025) documents that corruption increases clean cooking transition in Africa. In contrast, Acheampong (2023) utilise GMM on Africa's data between 2000 and 2017 to reveal that governance quality drags CCF in Africa. Shittu, Latiff, and Baharudin (2024) also report, using 65 emerging nations, that CCF is impeded by institutional quality.

In addition to studies on governance quality and CCF, we also included literature on governance and electrification and green energy. For instance, Kar and Swain (2023) appraise the effects of governance quality on electricity access in Africa and reported that governance quality expands the accessibility of electricity. This aligns with the submissions of Trotter (2016) and Sarkodie and Adams (2020) for Africa, showing the criticality of good governance in enhancing access to electricity. Huang, Ahmad, and Ali (2022) confirm that governance efficiency encourages the utilisation of clean energy in Asian nations. This also aligns with Vatamanu and Zugravu (2023), who indicate that institutional quality expands the utilisation of clean energy in European economies. Wang et al. (2022) also argue in favour of institutional quality, stimulating the transition to green energy in developed economies. This is also reechoed by Dossou et al. (2023) using data from Africa and the panel corrected standard error (PCSE) estimation technique. This indicates that the enhancement of the governance infrastructure is essential for stimulating the utilisation of sustainable energy. By contrast, other studies have shown that governance quality does not enhance green energy. For instance, Alinsato et al. (2024) establish that governance infrastructure is not essential for the transition to sustainable energy in Africa. This discovery is not unique, as Pan et al. (2022) also report the same outcome in Africa, revealing that the region's governance quality encourages the utilisation of conventional energy against green energy.

2.5. Literature gaps

The foregoing highlights that several voids still exist in the extant literature. First, the combined influence of public debt and governance quality on CCF remains unexplored. Hence, our study is the first to assess the effect of public borrowing and governance infrastructure on CCF in a single framework. Second, the limited literature on CCF is primarily based on panel studies that ignore country-specific characteristics. Given that panel studies may overlook the specific enablers or barriers that will stimulate policy decisions in a country, this study takes an individual country approach, focusing on Nigeria, which has high debt levels, poor governance infrastructure, and limited access to CCF. Third, previous studies employed either external debt or aggregate debt as a proxy for public borrowing. In some contexts, this could capture the exact debt level of an economy, but this is not the case for Nigeria, as the nation's debt level is predominately domestic. Hence, our study utilises disaggregated debt levels (domestic and external debt) to provide robust evidence for policy decisions. Fourth, prior studies have examined CCF at an aggregate level. To help Nigeria speed up their quest for clean cooking transition, we used disaggregated measures given the significant rural-urban disparity in CCF in Nigeria. Finally, we depart from the linear approach adopted by previous studies by utilising a nonlinear approach using the newly introduced quantile-on-quantile regression (QQR). This technique provides a holistic analysis of the connection between variables across diverse distributional quantiles, thereby obtaining heterogeneous and nonlinear impacts that otherwise will be ignored by conventional techniques. This approach is essential in environmental, energy, and public policy studies, where the nexus can be complex and differ across diverse levels of the variables considered. To the best of our knowledge, no prior research has employed QQR to evaluate the combined effects of governance and public debt on clean cooking transitions. This highlights a critical void in the literature, as QQR offers extensive insights into these connections across diverse quantiles of the variables utilised.

3. Methodology

3.1. Data

This study focuses on Nigeria, covering the period 2000:Q1 to 2022:Q4, because data for the dependent variables became available starting in 2000. The data were converted to quarterly intervals using the quadratic sum method in EView. Appendix 1 presents the sources of these variables. For the dependent variables, we followed the methodologies of Acheampong, Opoku, and Dogah (2023), Acheampong (2023), Dimnwobi et al. (2023c), Murshed (2023), and Okere et al. (2023b), utilising rural and urban clean cooking fuel access to account for the differences between remote and urban areas. In Nigeria, urban access to clean cooking fuel is 45.4%, whereas rural access is only 10.8% (World Bank 2023). For the explanatory variables, we align with Ezenekwe et al. (2023) and Nwokoye et al. (2024) using disaggregated debt stock, distinguishing between external debt sourced from foreign entities and domestic debt sourced locally. Additionally, adopting an approach similar to Okere et al. (2023a), Dossou et al. (2023), and Onuoha et al. (2023b), we employ six governance indicators to capture various dimensions of governance quality. These indicators include the rule of law, regulatory quality, governance effectiveness, control of corruption, political stability, and voice and accountability.

3.2 Analytical method

The Quantile-on-quantile method, as proposed by Sim and Zhou (2015), extends the traditional quantile regression (QR) approach, enabling researchers to examine the heterogeneous impacts of an independent variable across different quantiles of a dependent variable. The QQ method offers two significant advantages by combining conventional QR analysis with local linear nonparametric estimation. First, as a nonparametric estimation technique, it avoids the issue of misspecified functional forms that are common in parametric models. Second, unlike mean-based methods, such as OLS and traditional quantile regression, the QQ method is more robust to outliers and non-normality in the data. It excels in identifying potential structural changes and relaxing the linear model assumption inherent in traditional quantile regression, thus allowing for the possibility of nonlinear relationships between variables (Feng et al. 2023). The QQ technique enables a comprehensive examination of the entire dependence structure between public debt and governance infrastructure in the context of Nigeria's clean cooking transition by utilising various quantiles of their respective distributions.

Let the quantile of the clean cooking fuel growth rate be denoted by superscript θ. We modelled the relationship between clean cooking fuel and changes in public debt and governance infrastructure using the following nonparametric θ-quantile regression equation:

$$CCF_t = \beta_1^{\theta}(GI_t) + \beta_2^{\theta}(DEBT_t) + \varepsilon_t^{\theta} \tag{1}$$

GI_t represents the various governance infrastructures in the given period t, ε_t^{θ} is the residual term with a zero θ-quantile, $\beta_1^{\theta}(.)$ and $\beta_2^{\theta}(.)$ shows the impact of various governance infrastructures and debts (external and internal) on clean cooking gas. Meanwhile, because no prior information is available on the relationship between CCF, GI, and DEBT, β_1^{θ} and β_2^{θ} were assumed to be unknown functions.

To establish the relationship between the θ-quantile of clean cooking gas growth on the one hand and the τ_1 of various governance infrastructure and debt. Thus, the estimation of involves $\beta^{\theta}(.)$ following a first-order Taylor approximation can as expressed in the following Equation (2) below:.

$$\beta_1^{\theta}(GI_t) \approx \beta_1^{\theta}(GI^{\tau_1}) + \beta_1^{\theta'}(GI^{\tau_1})(GI_t - GI^{\tau_1}) \tag{2}$$

$$\beta_2^{\theta}(DEBT_t) \approx \beta_2^{\theta}(DEBT^{\tau_2}) + \beta_2^{\theta'}(DEBT^{\tau_2})(DEBT_t - DEBT^{\tau_2}) \tag{3}$$

where $\beta_1^{\theta'}$ and $\beta_2^{\theta'}$ in Equations (2) and (3) are the partial derivations of $\beta_1^{\theta}(GI^{\tau_1})$ and $\beta_2^{\theta}(DEBT^{\tau_2})$ in eqt. 2 and 3 respectively. Building on Sim and Zhou (2015), we assumed that $\beta_1^{\theta}(GI^{\tau_1})$, $\beta_1^{\theta'}(GI^{\tau_1})$, and $\beta_2^{\theta}(DEBT^{\tau_2})$, $\beta_2^{\theta'}(DEBT^{\tau_2})$ are both function of θ and τ, and can rewritten as thus of $\beta_0(\theta, \tau)$ and $\beta_1(\theta, \tau)$ in an indexrd form respectively. Therefore, Equations (2) and (3) can be expanded as follows:

$$\beta_1^{\theta}(GI_t) \approx \beta_1^{\theta}(\theta, \ \tau) + \beta_1^{\theta'}(\theta, \ \tau)(GI_t - GI^{\tau_1}) \tag{4}$$

$$\beta_2^{\theta}(DEBT_t) \approx \beta_2^{\theta}(\theta, \ \tau) + \beta_2^{\theta'}(\theta, \ \tau)(DEBT_t - DEBT^{\tau_2}) \tag{5}$$

Through substitution, we incorporated Equations (4) and (5) into Equation (1) to obtain

$$CCF_t = \underbrace{\beta_0^{\theta}(\theta, \ \tau_1, \tau_2) + \beta_{11}^{\theta'}(\theta, \tau_1)(GI_t - GI^{\tau_1}) + \beta_{21}^{\theta'}(\theta, \ \tau_2)(DEBT_t - DEBT^{\tau_2})}_{(*)} + \varepsilon_t^{\theta} \tag{6}$$

Part (*) of Equation (6) captures the overall dependence structure between CCF and both GI and debt by incorporating the dependence between their respective distributions.

Accordingly, Equation (6) GI_t is replaced by its estimated value $\widehat{GI}_t$, $DEBT_t$ is replaced by its estimated value $\widehat{DEBT}_t$. Similarly, GI^{τ_1} is replaced by its estimated value, and $\widehat{GI}_t^{\tau_1}$ and $DEBT^{\tau_2}$ are replaced by its estimated value $\widehat{DEBT}_t^{\tau_2}$.

$$\boldsymbol{MIN}_{\boldsymbol{\beta}_0\boldsymbol{\beta}_{11}} \sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} \boldsymbol{\rho_\theta}[CCF_{it} - \beta_0 - \beta_{11}(\theta, \tau_1)(GI_t - GI^{\tau_1}) - \beta_{21}(\theta, \ \tau_2)(DEBT_t - DEBT^{\tau_2})]K\left(\frac{F_n(\widehat{GI}_t) - \tau}{h}\right) \tag{7}$$

$$\boldsymbol{MIN}_{\boldsymbol{\beta}_0\boldsymbol{\beta}_{21}} \sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} \boldsymbol{\rho_\theta}[CCF_{it} - \beta_0 - \beta_{11}(\theta, \tau_1)(GI_t - GI^{\tau_1}) - \beta_{21}(\theta, \ \tau_2)(DEBT_t - DEBT^{\tau_2})]K\left(\frac{F_n(\widehat{DEBT}_t) - \tau}{h}\right)$$

First, $\beta_0(\theta, \tau_1, \tau_2)$, $\beta_{11}(\theta, \tau_1)$, $\beta_{21}(\theta, \tau_1)$ can be estimated, where ρ_θ is the function that provides the $\theta-$conditional quantile of CCG_{it} as the solution. We focus on the impact of τ_1-quantiles GI and $\tau_2 - quatiles$ of Debt. Second, the Gaussian kernel $K(.)$ was adopted to verify the role of $\widehat{GI}_t^{\tau_1}$, with the bandwidth generated by h. These weights are inversely related to the $(\widehat{GI}_t)$, $\widehat{GI}_t^{\tau_1}$ and their counterparts with $\widehat{DEBT}_t^{\tau_1}$

$$F_n(\widehat{GI}_t) = \frac{1}{n}\sum_{k=1}^{n} I(\widehat{GI}_k < \widehat{GI}_\tau) \tag{8}$$

$$F_n(\widehat{DEBT}_t) = \frac{1}{n}\sum_{k=1}^{n} I(\widehat{DEBT}_k < \widehat{DEBT}_\tau) \tag{9}$$

The rule-of-thumb method is a common approach for bandwidth selection, which often assumes an underlying Gaussian density. First, this method provides a straightforward way to estimate the bandwidth, but may not always yield optimal results, especially for non-Gaussian data distributions. In this investigation, a plug-in bandwidth of h = 0.05 h = 0.05h = 0.05 was utilised, as recommended by Sim and Zhou (2015). Second, selecting an appropriate bandwidth is crucial in density estimation because it directly influences the accuracy of the results. Thus, a narrower bandwidth minimises bias but increases variance, which can lead to over-smoothing and the loss of important data features. On the other hand, a wider bandwidth reduces variance, but may introduce higher bias, potentially causing undersmoothing and inaccuracies in estimating the underlying density. Therefore, striking a balance between bias and variance is critical for ensuring precise and reliable estimation without compromising key data characteristics (Chan, Lee, and Peng 2010; Park and Marron 1990).

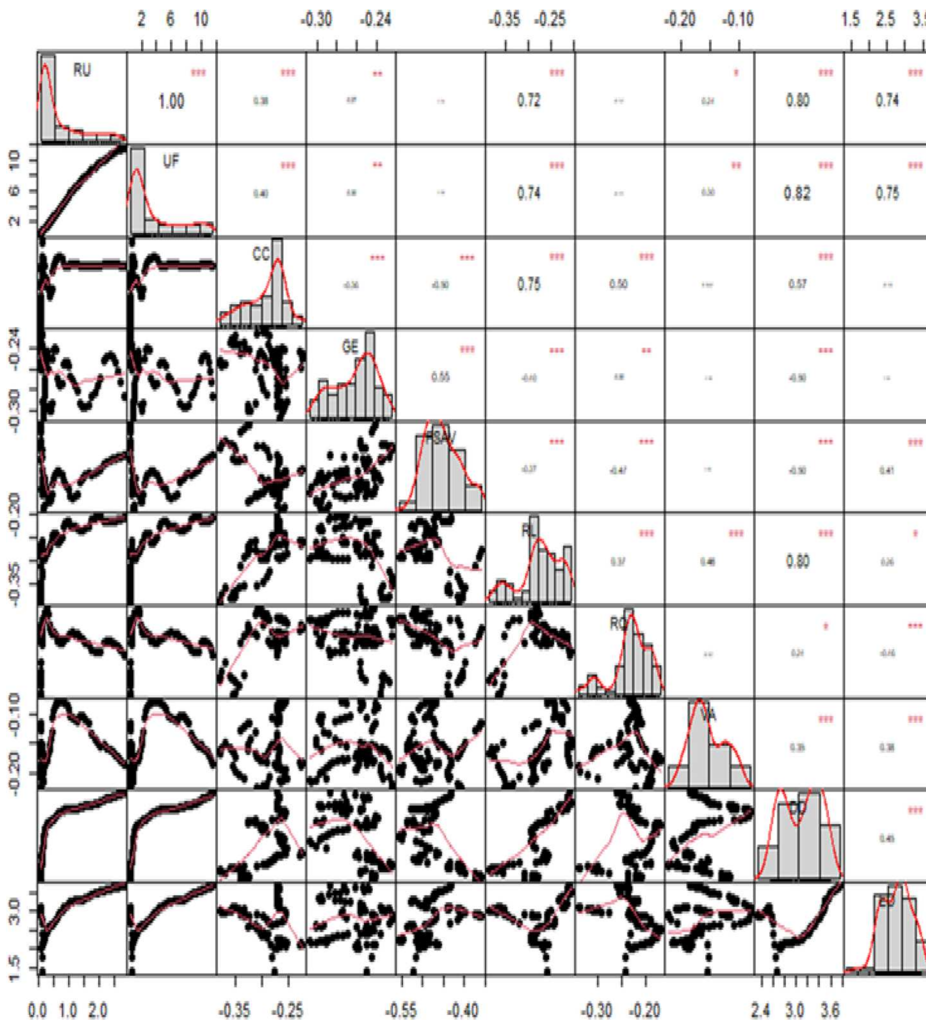


Figure 2. Correlation map. Source: Excerpt from R Studio.

4. Analysis and interpretation of findings

4.1. Prelimainary results

The correlation map in Figure 2 provides a visual representation that allows a snapshot assessment of whether the data are normally distributed or skewed.

Figure 2 above reports the correlation matrix displays numerical correlation coefficients that indicate the strength and direction of the relationships between pairs of variables. Some variables, such as rural (RU), urban (UF) access to clean cooking and control of corruption (CC), exhibited strong positive correlations,

Table 1. Descriptive statistics.

Variables	Mean	Median	Std. Dev.	Skewness	Kurtosis	JB
CC	−0.2906	−0.2737	0.0367	−0.6767	2.7271	7.3065***
DD	3.0534	3.1482	0.4503	−0.0941	1.5664	8.0135***
ED	2.7972	2.8811	0.5113	−0.1608	2.3487	2.0224**
GE	−0.2604	−0.2557	0.0224	−0.4365	2.0901	6.0956***
PSAV	−0.4688	−0.4748	0.0515	0.5060	2.4590	5.0480***
RL	−0.2753	−0.2711	0.0496	−0.6326	2.6829	6.5210***
RQ	−0.2258	−0.2213	0.0397	−0.9786	3.6580	16.3440***
RU	0.6120	0.1992	0.7748	1.5156	4.0553	39.4891***
UF	3.0158	1.0977	3.4516	1.3001	3.2440	26.1445***
VA	−0.1542	−0.1623	0.0401	0.3661	2.0890	5.2360***

Note: *, **, *** significant at 10%, 5%, 1%. source: Excerpt from R Studio.

with coefficients around 0.72–0.82, signifying a significant linear association. By contrast, certain pairs, such as political stability and absence of violence/terrorism (PSAV) and regulatory quality (RQ) or rule of law (RL) and CC, demonstrate negative correlations, implying that as one variable increases, the other tends to decrease. Second, beneath the diagonal, some scatter plots display a clear linear pattern, while others suggest more complex, nonlinear dependencies that may not be fully captured by the correlation coefficients alone; therefore, highlighting areas where further investigation may be necessary, particularly when nonlinearity is evident.

Table 1 summarises the descriptive statistics of the study variables, highlighting their central tendency, dispersion, and distributional properties. Most governance-related indicators, such as Government effectiveness (GE) (−0.2604), Voice and Accountability (VA) (−0.1542), CC (−0.2906), and PSAV (0.4688), exhibit negative mean values, suggesting below-average performance. Conversely, RU (0.6120) and UF (3.0158) showed positive mean values, indicating significant variability. Standard deviation analysis revealed that UF (3.4516) and RU (0.7748) had the highest variability, whereas GE (0.0224) and CC (0.0367) were more stable. The skewness and kurtosis results indicate that most governance indicators are left-skewed, whereas RU (1.5156) and UF (1.3001) are right-skewed, suggesting occasional extreme increases. Jarque-Bera (JB) tests confirmed non-normality ($p < 0.01$) for all variables. The quantile unit root test results presented in Appendix 2 provide a detailed view of the stationarity properties of various clean cooking indicators and public debt and governance infrastructure in Nigeria, evaluated across different quantiles using the Koenker and Xiao (2004) framework. As shown by t-statistics falling below the 5% critical value (red line). However, the degree of stationarity varies across the distribution, with some quantiles showing non-stationarity where t-statistics lie above the red line. This reflects asymmetric adjustment speeds and highlights distributional differences in the indicators' time-series behaviour. These findings provide a strong foundation for econometric modelling to examine the relationships among variables, especially their potential nonlinear and heterogeneous effects.

Table 2 reports the results of the nonlinearity test based on the BDS under the null hypothesis for the test that supports that the independent and identically distributed (*iid)* of the residuals could not hold. Thus, it can be concluded that the relationship examined in this study is nonlinear. This finding is further supported by descriptive statistics, which reveal a non-normal data distribution characterised by significant skewness and kurtosis, along with indications of fat-tailed behaviour. In summary, the presence of potential asymmetries in the relationship under investigation strongly justifies the application of the QQR methodology. This approach is particularly well-suited for capturing and analysing such complexities.

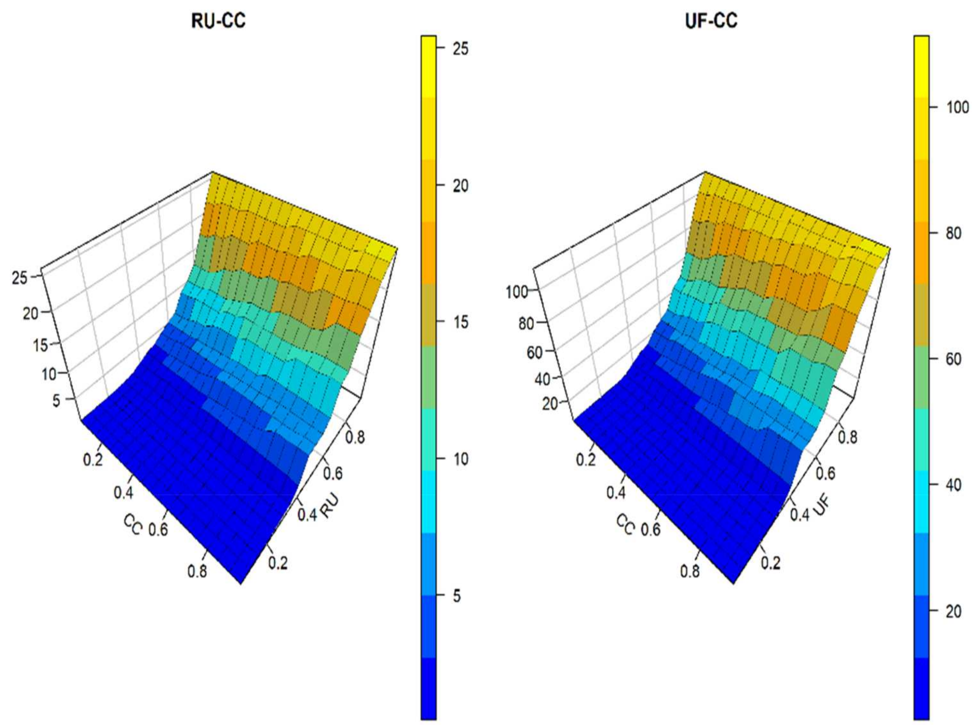
4.2. Quantile-on-quantile (QQR) results

The preceding section analysed descriptive statistics, which highlighted several important features of the data series, such as non-normality and heavy-tailed distributions. Given these characteristics, the quantile regression framework was identified as the most appropriate analytical method. This approach is particularly effective in capturing the asymmetric effects of the independent variables – governance infrastructure and debt – across various quantiles of the dependent variable, CCF (Figures 3–10). The analysis is

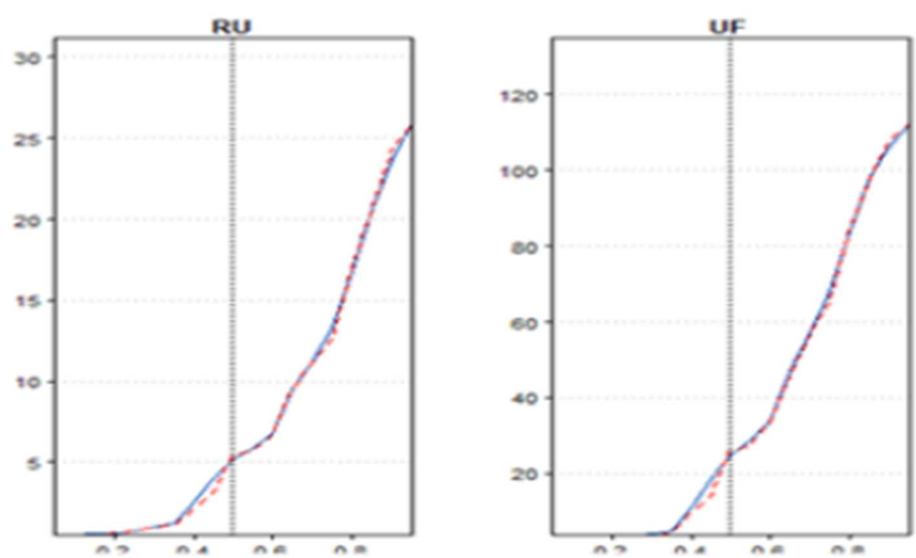
Table 2. BSD test.

Variables	M2	M3	M4	M5	M6
CC	0.1800***	0.2984***	0.3752***	0.4190***	0.4420***
DD	0.2058***	0.3483***	0.4478***	0.5177***	0.5682***
ED	0.1801***	0.2970***	0.3725***	0.4209***	0.4490***
GE	0.1377***	0.2224***	0.2676***	0.2859***	0.2879***
PSAV	0.1759***	0.2920***	0.3665***	0.4111***	0.4375***
RL	0.1728***	0.2860***	0.3565***	0.3976***	0.4203***
RQ	0.1634***	0.2670***	0.3314***	0.3678***	0.3850***
RU	0.1879***	0.3101***	0.3906***	0.4440***	0.4789***
UF	0.1892***	0.3134***	0.3960***	0.4516***	0.4888***
VA	0.1755***	0.2915***	0.3663***	0.4114***	0.4362***

***, **, * signify the 1%, 5%, & 10%. source: Excerpt from R Studio.



a



b

Figure 3. Quantile-on-quantile (QQR) graph between clean cooking transition and governance quality. Source: Excerpt from R Studio.

divided into two parts: the first presents the main model estimation, while the second evaluates the robustness of the results using the traditional quantile regression approach[1] to validate the Quantile-on-Quantile method.

(I) Quantile-on-quantile (QQR) results: Governance Infratructure and CCF
(a) CC impact on RU and UF

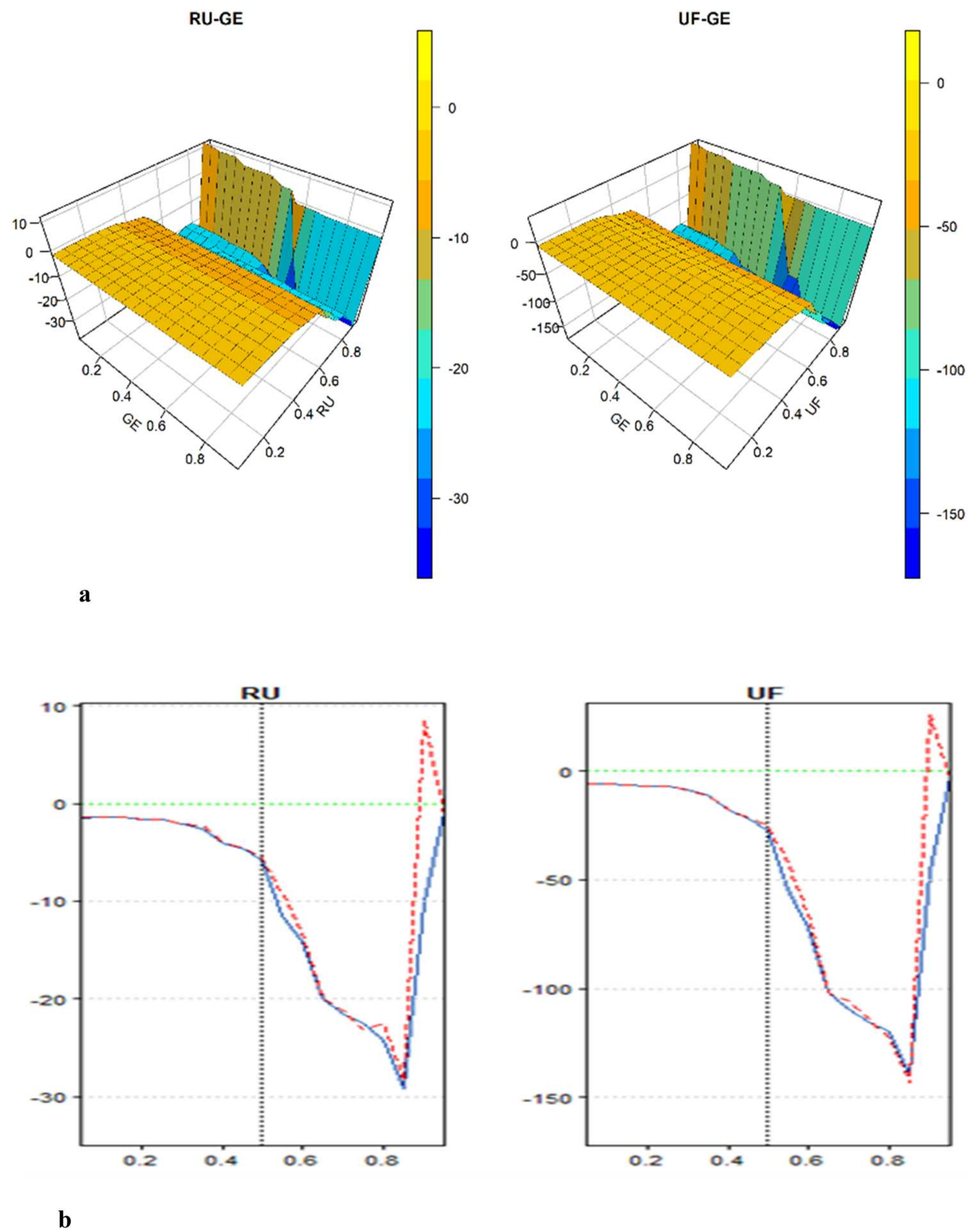


Figure 4. Quantile-on-quantile (QQR) graph between clean cooking transition and governance quality. Source: Excerpt from R Studio.

Figure 3 presents the slope coefficients estimated using the QQR method, clearly illustrating the asymmetric effect of CC on the RU and UF. Specifically, the results indicate a consistently positive marginal effect of CC on RU and UF across all quantiles of CC distribution. This effect is relatively lower at the lower quantiles (0.05–0.10 for RU and 0.20–0.40 for UF), increases around the median quantiles, and continues to rise at higher quantiles (0.15–0.25 and 0.60–1.00, respectively). These findings suggest that the impact of CC on RU is more pronounced when the CC is at its optimal level. To ensure robustness, we also applied the conventional Quantile Regression (QR) method, and the results are displayed in Figure 3. The graph illustrates the average coefficient for each quantile derived from the QR analysis, revealing a consistently positive and increasing impact of CC on the RU and UF.

(b) GE impact on RU and UF

In GE-RU, Figure 4 ranges between – 30 and 0, with a relatively smooth transition across the lower quantiles. However, as the quantiles increased, a sharp decline emerged, indicating a structural shift in the

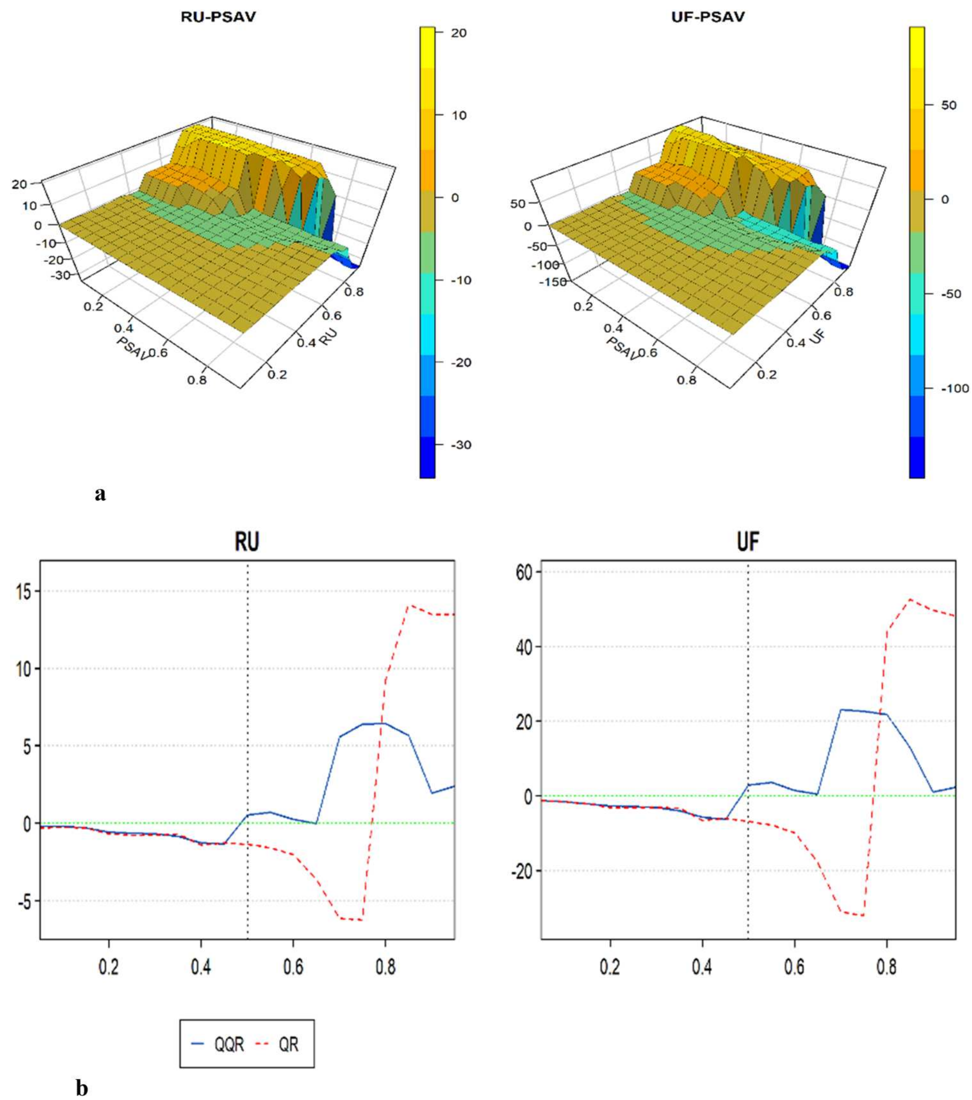


Figure 5. Quantile-on-quantile (QQR) graph between clean cooking transition and governance quality. Source: Excerpt from R Studio.

relationship. This suggests that, while lower quantiles exhibit a weakly negative effect, higher quantiles introduce stronger deviations, possibly reflecting a point beyond which the impact of GE on RU intensifies dramatically. On the other hand, GE-UF shows a similar but broader range of values, from – 150–0. The steep decline at higher quantiles is more pronounced than that in the GE-UF plot, underscoring a more extreme alteration in the relationship. The colour gradient in the GE-UF plot accentuates this difference, with deeper blue shades highlighting the intensity of negative values. Meanwhile, the robustness check in Figure 4 indicates that both RU and UF plots become increasingly negative as the quantiles progress from 0.2–0.7. This pattern closely aligns with the sharp declines observed in Figure 4, confirming that the negative impact intensifies at these mid-range quantiles. Specifically, the UF plot shows a much stronger Fcorr impact, reaching values as low as – 150, compared to – 30 in the RU plot. This corroborates the findings from the previous graph, indicating that GE exerts a more pronounced influence on the RU variable than on the UF.

(c) PSAV impact on RU and UF

In the PSAV-RU in Figure 5, the values range between −30 and 20, indicating a moderate variation in effects. At lower quantiles (0.2–0.4), the relationship remains relatively stable, with values clustering around 0 to −10. However, as the quantiles increased beyond 0.6, the surface exhibited notable fluctuations, with

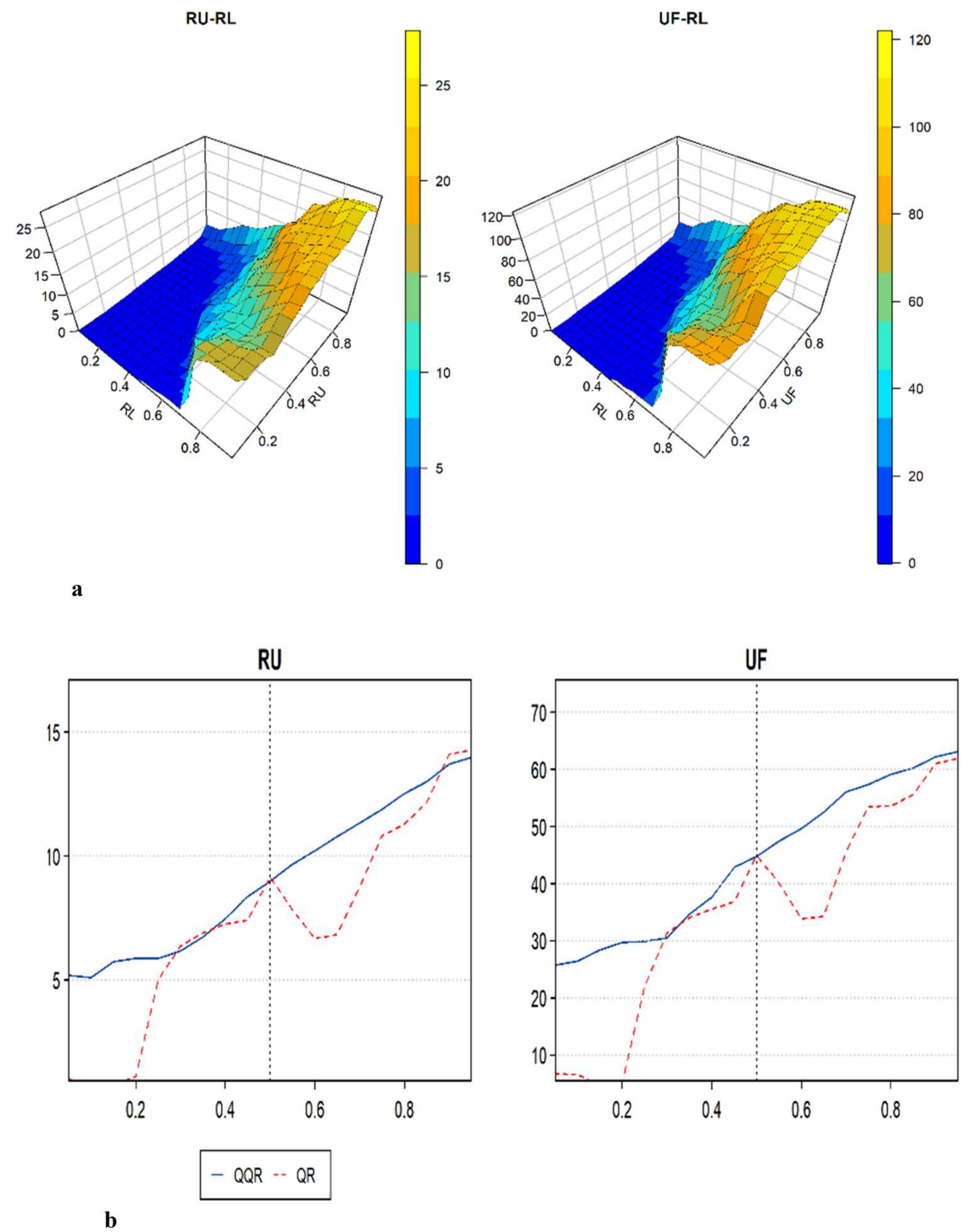


Figure 6. Quantile-on-quantile (QQR) graph between clean cooking transition and governance quality. Source: Excerpt from R Studio.

sharp changes in the gradient and increasing dispersion of values. This suggests a potential nonlinear effect, where the impact of PSAV on RU becomes more volatile at higher quantiles (0.6–1.00). Distinct ridges and abrupt shifts may indicate a threshold effect, where changes in PSAV lead to pronounced variations in RU beyond a certain quantile range. In addition, the PSAV-UF plot displays a much broader range of values, spanning from −150 to 50, signifying a more pronounced effect compared to PSAV-RU. Similar to the RU-PSAV case, the lower quantiles exhibited a relatively stable trend, albeit at a more negative level. The sharp transitions and irregular peaks suggest heightened sensitivity of PSAV to UF at higher quantiles, reinforcing the notion of a nonlinear, threshold-driven relationship. In the sensitivity analysis, Figure 5 reinforced the observations in Figure 5 by revealing a pronounced divergence in behaviour across different quantiles, with the most striking variations occurring beyond the 0.7 quantile.

(c) RL impact on RU and UF

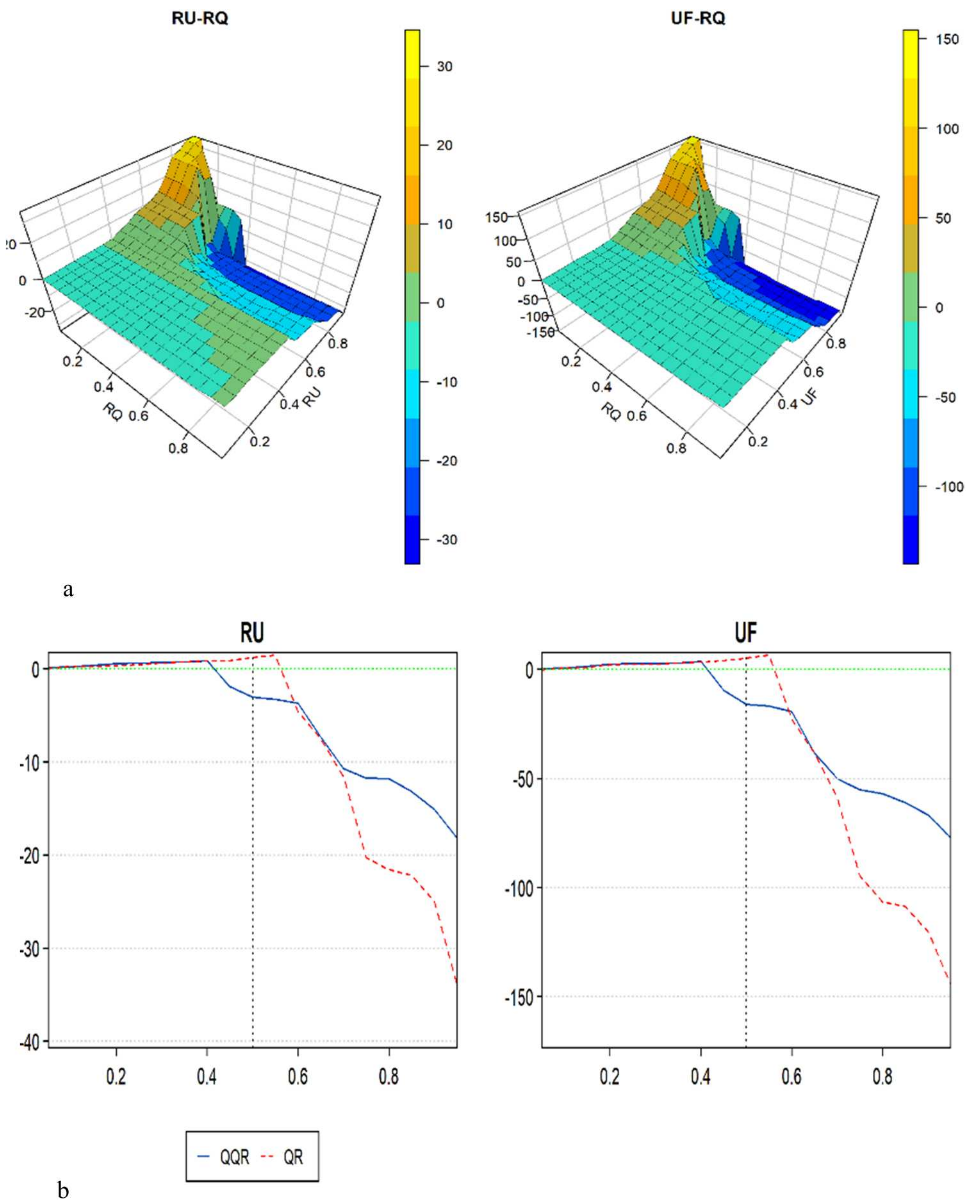


Figure 7. Quantile-on-quantile (QQR) graph between clean cooking transition and governance quality. Source: Excerpt from R Studio.

Figure 6 shows that the RU-RL relationship suggests a gradual increase in RL as RU moves from lower to higher quantiles. However, a noticeable shift occurs beyond the 0.6 quantile, where RL begins to increase sharply. This trend indicates that the impact of RL on RU is relatively stable at lower quantiles but becomes significantly more pronounced in higher quantiles. The transition from blue to yellow and orange highlights the threshold effect, where RU exhibits sudden amplification once RL crosses a certain threshold. In contrast, the UF in Figure 6 remains relatively stable at lower quantiles (0.2–0.4) of RL; it undergoes a rapid increase once RL exceeds the 0.6–0.8 range. The steeper slope compared to RU-RL suggests that RL has a stronger and more volatile impact on UF, with UF values exceeding 100 at the upper quantiles of RL. This pattern reinforces the idea that UF responds disproportionately to changes in RL, particularly under extreme conditions. In Figure 6, both RU and UF display a more consistent and steadily increasing trend across quantiles, with QQR (blue line) maintaining a nearly linear trajectory. By contrast, the QR estimates (red dashed line) exhibit noticeable deviations, particularly around the middle quantiles (0.4–0.6),

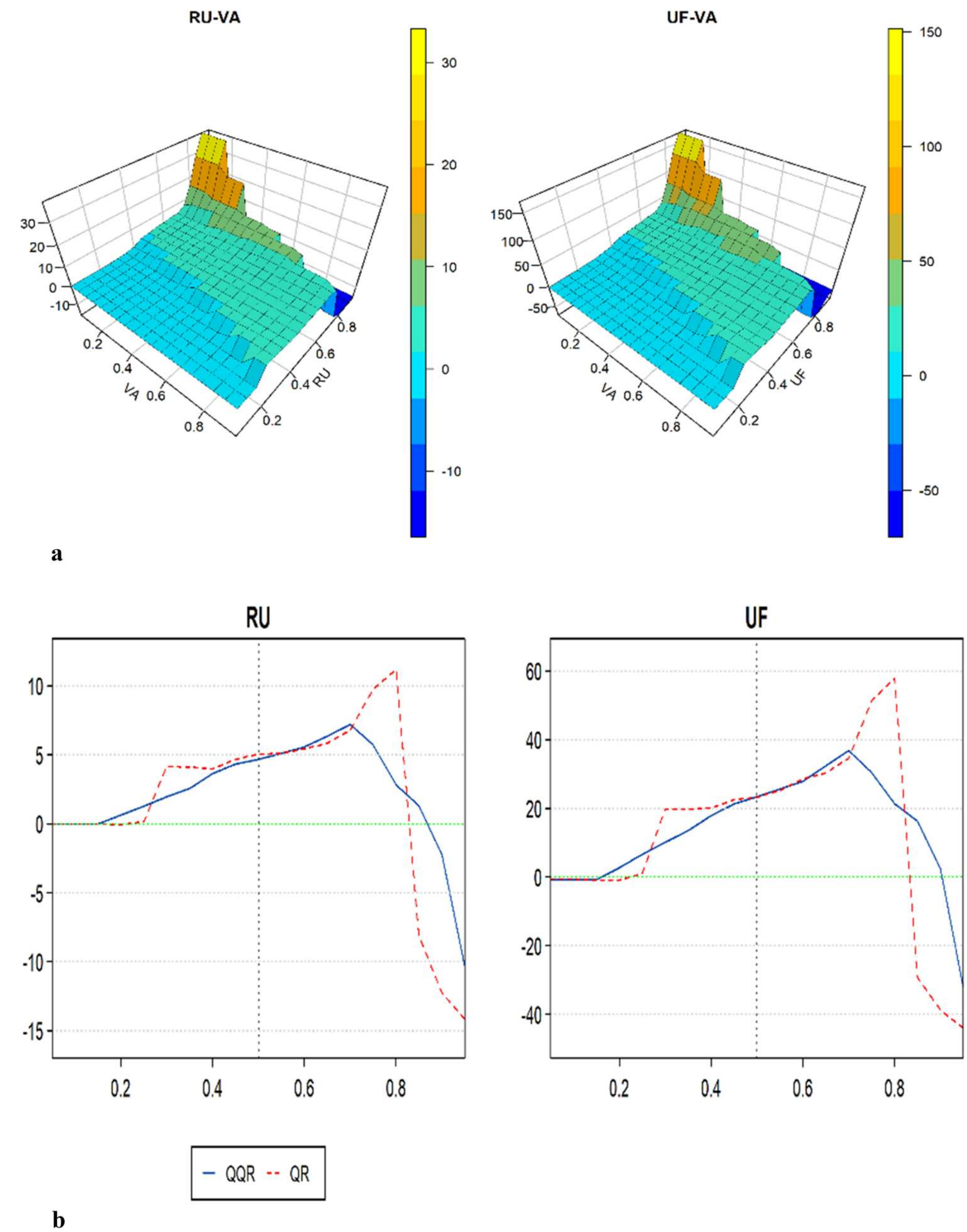


Figure 8. Quantile-on-quantile (QQR) graph between clean cooking transition and public debt. Source: Excerpt from R Studio.

where fluctuations emerge before stabilising. At higher quantiles, the RU and UF follow a more predictable and gradual upward pattern, reinforcing the overall trend of monotonic growth.

(e) RQ impact on RU and UF

In Figure 7, the transition from blue to yellow and orange highlights the pronounced threshold effect. Initially, at lower quantiles, the relationship remained relatively stable, with RU and UF maintaining consistent patterns. However, as the quantiles increase, there is a sharp upward shift, indicating a nonlinear relationship, where RU and UF exhibit sudden amplification in response to RQ. This suggests that beyond a certain threshold, the effect of RQ on RU and UF intensifies significantly. The presence of negative values in the lower quantiles, represented by the blue regions, indicates a possible suppression effect at lower levels, which gradually transitions into positive values as the quantiles increase. The sharp peaks in the yellow and orange regions signify a critical inflection point, where the relationship strengthens, reinforcing the idea of a threshold-dependent effect. Examining the quantile regression curves in Figure 7, a more detailed breakdown of this effect emerges. At lower

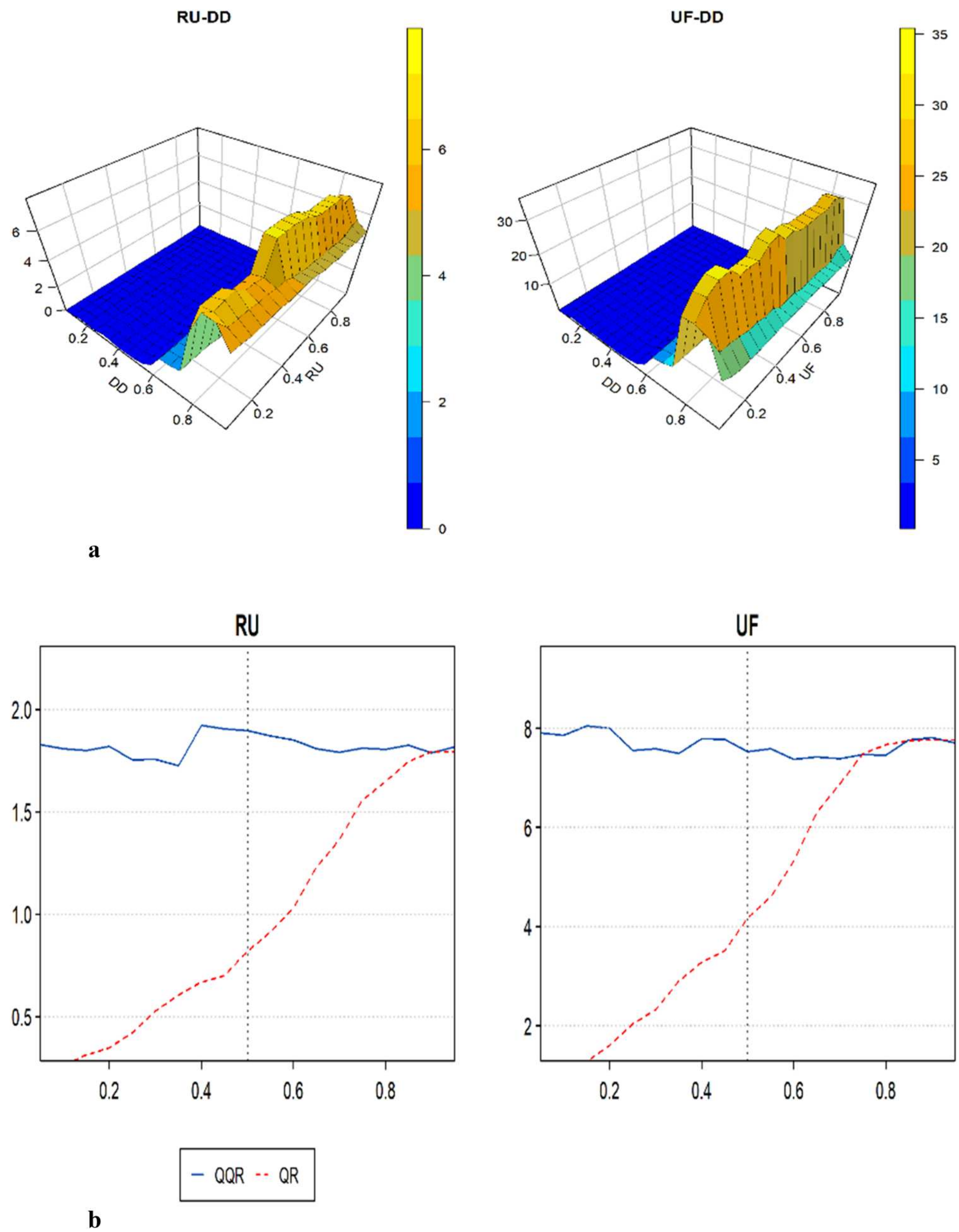


Figure 9. Quantile-on-quantile (QQR) graph between clean cooking transition and public debt. Source: Excerpt from R Studio.

quantiles, both RU and UF displayed stability, with little deviation from the baseline. However, beyond the median quantile (0.5), a sharp decline was observed, reinforcing the threshold behaviour observed in the Figure 7 representations. This suggests that, while the impact of RQ is minimal in the lower half of the distribution, it becomes increasingly negative in the upper quantiles, ultimately leading to a substantial downturn.

(f) VA impact on RU and UF

In the case of RU-VA in Figure 8, the relationship appears relatively stable at lower quantiles, with values predominantly in the blue to light-green range. This suggests that at the lower end of the distribution, VA exerts only a minimal or neutral effect on RU. However, as we move towards the middle quantiles, a transition becomes evident with a moderate increase in RU. The most striking observation emerged at higher quantiles, where RU exhibited a sharp increase, marked by the presence of yellow and orange hues. A similar trend was observed for the UF-VA relationship. At lower quantiles, UF remained largely stable, displaying minor fluctuations that aligned with the lower-bound behaviour of RU. However, as we progress to the

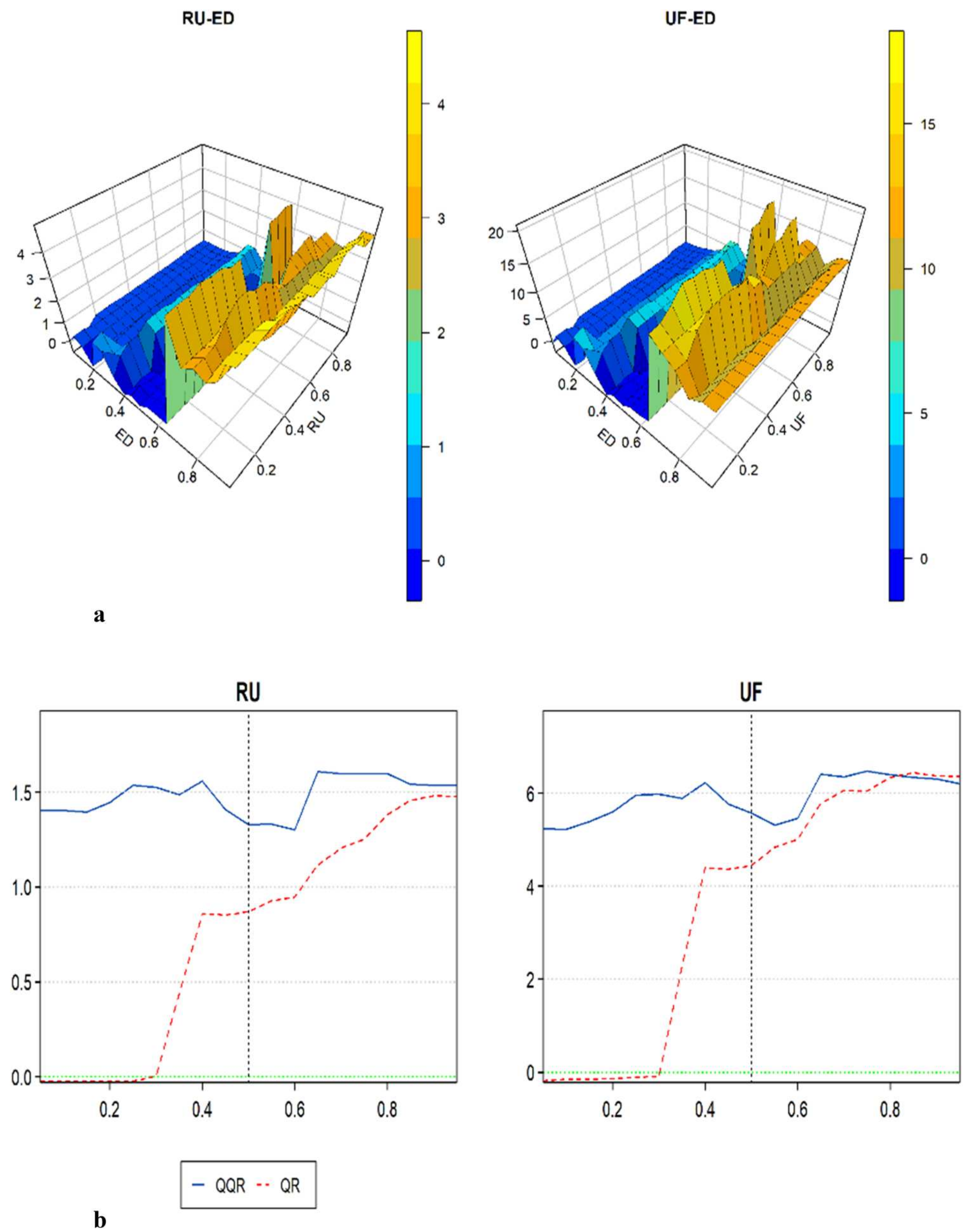


Figure 10. Quantile Granger causality test. Source: Excerpt from R Studio.

middle quantiles, the UF begins to respond more sensitively to VA, marking the onset of a more noticeable effect. The most dramatic shift occurs in the higher quantiles, where UF experiences a substantial increase, mirroring the pattern seen in RU. In contrast to the earlier findings in Figure 8, where the quantile regression (QR) and quantile-quantile regression (QQR) estimates exhibited a steep and continuous decline at higher quantiles, the results in Figure 8 show a more structured trajectory where RU displays a gradual increase from lower quantiles up to approximately 0.7 mark before experiencing a sharp downward shift. This differs from previous results, in which the decline began earlier and was more abrupt. Similarly, in the case of UF, the trend remains upward until around the 0.8 quantile, after which a sudden drop is observed. Notably, this suggests that observations in the upper tail are more sensitive to variations, an effect that is less pronounced in the results shown in Figure 8.

(ii) Quantile-on-quantile (QQR) results: Public Debt and CCF

(a) DD impact on RU and UF

The quantile regression results in Figure 9 for RU-DD and UF-DD reveal distinct patterns in the distribution effects of the explanatory variables. For RU-DD, at lower quantiles (below 0.4), the dependent variable, RU, remains relatively stable, with values close to zero. However, as the quantile increases beyond 0.4, there is a noticeable rise in the impact, reaching a peak near 0.8. This pattern indicates that, at higher quantiles, the effect of DD becomes more pronounced, with an increasing trend leading to a sharper change beyond the mid-range quantiles. The steep rise suggests a nonlinear relationship, where the impact is minimal at lower levels but strengthens as the distribution moves towards the upper quantiles. A similar trend is observed for UF-DD, where, at lower quantiles, the response remains subdued, showing near-zero effects. However, after crossing the 0.4 threshold, the dependent variable experienced a rapid increase, with steeper slopes observed compared to RU-DD. The effects are particularly strong beyond the 0.6 quantile, where the dependent variable exhibits an exponential-like rise, peaking around 0.9. This suggests that UF has a more substantial influence on the outcome variable at higher quantiles, emphasising a threshold effect where the impact becomes increasingly dominant in the upper tail of the distribution. In the robust check, Figure 9. presents a smoother and more gradual rise, reducing abrupt shifts. RU exhibits a more stable trajectory, whereas UF shows a more linear trend, suggesting a more evenly distributed impact across quantiles.

(b) ED impact on RU and UF

The Figure 10 quantile regression (QR) graphs for RU-ED and UF-ED illustrate the heterogenous effects across different quantiles. The colour gradients indicate the intensity of the relationship, with lower values in blue and higher values in yellow. For RU-ED, the graph shows a relatively stable trend at lower quantiles, with noticeable increases in the impact at higher quantiles. The transition from blue to yellow suggests that the effect strengthened as the quantile level increased. However, there are some fluctuations in the mid-quantiles, which might indicate variations in the relationships at different levels. In contrast, the UF-ED graph displays a more pronounced effect across the quantiles, with a steeper increase towards the upper quantiles. The higher peaks and greater variability indicate that the impact is more substantial at higher

Table 3. Quantile Granger causality test.

τ	0.10	0.25	0.50	0.75	0.90
tstat_star.x	7.74***	3.84***	1.74**	0.93	0.53
tstat_star.y	0.88	1.27	1.21	1.48*	0.98
tstat_star.x	0.67	1.21	0.59	1.00	0.54
tstat_star.y	0.6	0.94	0.86	1.00	0.61
tstat_star.x	10.14***	5.26***	1.96**	0.63	0.65
tstat_star.y	1.13	1.62*	1.43*	1.48*	0.45
tstat_star.x	0.49	1.17	0.63	0.73	0.26
tstat_star.y	0.51	1.38*	0.61	0.75	0.3
tstat_star.x	8.12***	4.25***	2.76***	1.33*	0.48
tstat_star.y	0.87	1.76**	2.14**	2.19**	0.83
tstat_star.x	0.68	0.78	0.9	0.56	0.28
tstat_star.y	0.75	0.77	1.27	0.74	0.35
tstat_star.x	5.56***	3.32***	2**	1.29	0.39
tstat_star.y	0.56	1.49*	0.97	1.26	0.81
tstat_star.x	0.29	0.58	0.48	0.26	0.3
tstat_star.y	0.38	0.63	0.78	0.25	0.4
tstat_star.x	6.85***	3.56***	1.77**	1.11	0.74
tstat_star.y	0.8	1.37*	0.98	1.31*	0.61
tstat_star.x	0.51	0.5	1.02	0.53	0.38
tstat_star.y	0.67	0.63	0.92	0.61	0.33
tstat_star.x	6.97***	3.08***	1.8**	0.91	0.45
tstat_star.y	0.71	1.94**	1.21	1.28	0.8
tstat_star.x	0.64	0.7	0.75	0.79	0.23
tstat_star.y	0.58	0.75	0.95	0.82	0.27
tstat_star.x	14.59***	8.76***	3.6***	1.57*	0.59
tstat_star.y	0.63	1.41*	1.02	0.94	0.55
tstat_star.x	0.55	0.59	1.39*	0.92	0.31
tstat_star.y	0.67	0.5	1.33*	0.91	0.31
tstat_star.x	9.12***	3.74***	2.71***	1.12	0.57
tstat_star.y	0.91	1.18	1.36*	1.08	0.4
tstat_star.x	1.47*	1.81**	1.17	0.68	0.26
tstat_star.y	1.52*	1.93**	1.13	0.88	0.28

***, **, * signify the 1%, 5%, & 10%. source: Excerpt from R Studio.

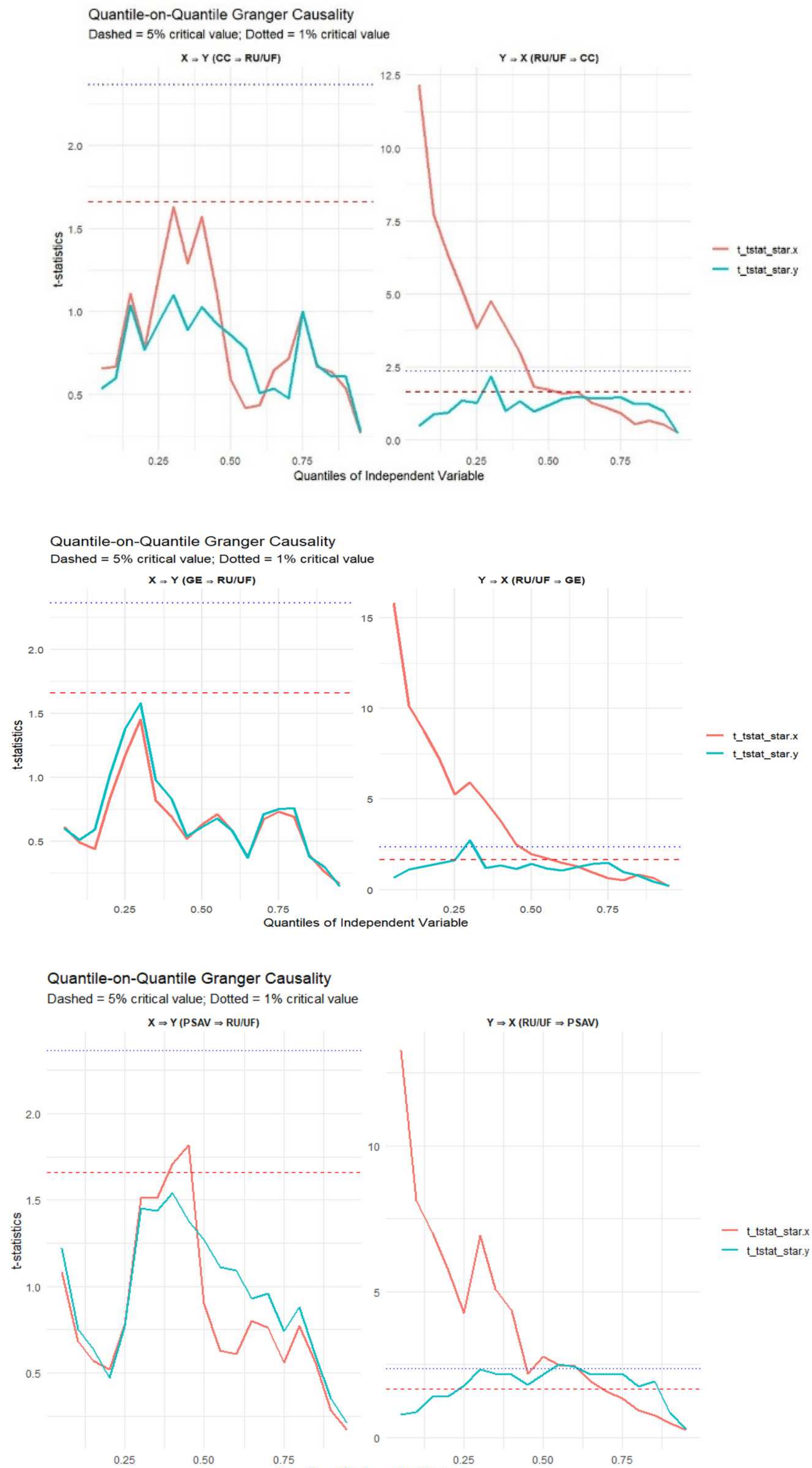


Figure 11. Quantile Granger causality test. Source: Excerpt from R Studio.

quantiles compared with RU-ED. Based on the robustness test, Figure 10 reveals that RU and UF display more distinct peaks and declines, especially beyond the 0.8 quantile, where the estimates experience a sharp increase followed by a significant drop. This indicates greater sensitivity at extreme quantiles, a feature that is less apparent in Figure 10. The QQR line mirrors the pattern observed in QR but with smoother transitions, suggesting an improvement in the precision of the estimates.

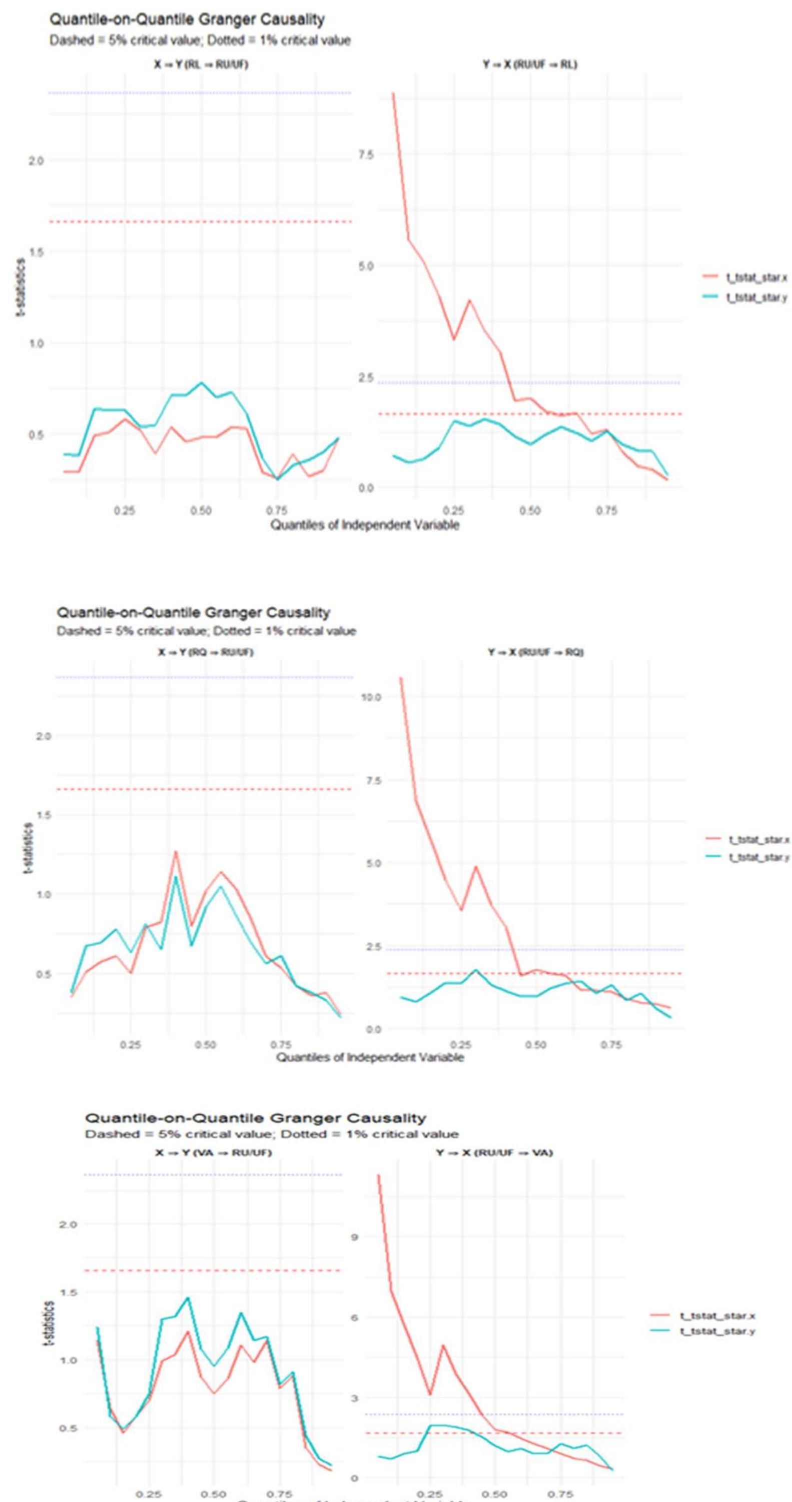
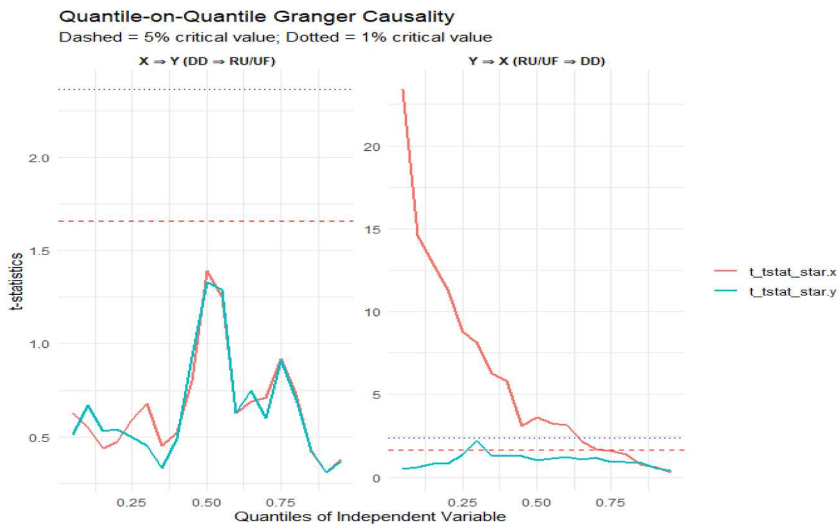


Figure 11. *Continued.*

4.3. Granger causality in quantiles

The Granger causality analysis is shown in Table 3 and Figure 11 for the quantiles reveal important insights into the dynamic relationships between clean cooking access (Y), governance infrastructure and public debt (X). Notably, there is strong evidence of directional causality from X to Y across the lower and median quantiles (τ = 0.10–0.50). This indicates that governance infrastructure and public debt (X) Granger-causes



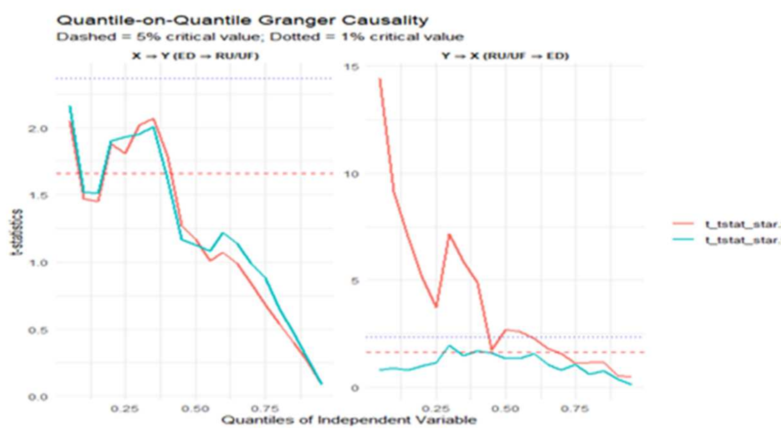


Figure 11. *Continued.*

Table 4. Quantile Autoregressive Distributed Lag (QARDL).

Variable	τ =0.1	τ =0.25	τ =0.5	τ =0.75	τ =0.90
Dependent variable RU					
(Intercept)	0.185**	0.209**	0.265**	0.197	0.208**
RU_lag	0.052***	0.070***	0.085***	0.045**	0.044**
AVGOV_lag	0.693**	0.754**	0.948**	0.719	0.746*
TPD_lag	−0.244**	−0.293**	−0.366**	−0.183	−0.172*
INTER_lag	−0.887**	−1.020**	−1.267**	−0.705	−0.674**
dAVGOV	−0.348	−0.001	0.592	0.544	−0.024
dTPD	0.242	0.112	−0.143	0.045	0.163
dINTER	0.763	0.148	−0.747	−0.118	0.514
Dependent variable UF					
(Intercept)	0.377	0.911**	1.263**	1.466*	0.960
UF_lag	0.077***	0.062***	0.082***	0.061**	0.050**
AVGOV_lag	1.393	3.270**	4.468***	5.208**	3.435
TPD_lag	−1.054**	−1.315***	−1.760***	−1.362	−0.618
INTER_lag	−3.413**	−4.538***	−6.013***	−4.912	−2.396
dAVGOV	−0.254	0.447	2.907	5.202	4.937
dTPD	0.096	−0.316	−1.061	−1.193	−0.858
dINTER	0.407	−1.402	−4.139	−5.175	−3.889

Note: *, **, *** significant at 10%, 5%, 1%. source: Excerpt from R Studio

clean cooking access (Y) primarily when Y is in a lower or typical state, suggesting that shocks to X have a more pronounced effect on Y under such conditions. In contrast, evidence of reverse causality – from Y to X – is observed only at moderate quantiles (τ = 0.25–0.75), and even then, the relationship is less consistent and statistically weaker. This suggests that while Y may influence X in certain cases, the effect is more localised and not as robust as the forward causality. In all, the presence of significant effects at lower quantiles that diminish toward the upper tail of the distribution highlights a clear pattern of asymmetry and heterogeneity. The results underscore that Granger causality is not constant across the distribution; rather, it is stronger when the dependent variable is at lower or median levels and weak or absent in higher quantile ranges.

Table 4 results presented for both Rural (RU) and Urban (UF) clean cooking access provide insights into how the effects of governance infrastructure (AVGOV), total public debt (TPD), and their interaction (INTER) vary across the conditional distribution (quantiles) of the dependent variables. In the long-run dynamics, both rural and urban access to clean cooking are positively influenced by improved governance and negatively affected by rising public debt. The interaction term (INTER), capturing the combined effect of governance and debt, is consistently negative across quantiles, indicating that high levels of public debt significantly weaken the positive impact of governance on clean energy access. These effects are more pronounced in the long run and vary across the distribution, with lower and middle quantiles, typically representing more disadvantaged populations being more vulnerable to the adverse effects of debt. Notably, these findings are consistent with the non-parametric results previously established, reinforcing the robustness of the Quantile ARDL estimates. In contrast, short-run effects are generally insignificant, suggesting that policy reforms in governance and debt management may require time to yield tangible improvements in clean cooking access.

4.4. Discussion of empirical findings

One of the central research questions in this study is: *Do governance infrastructure stimulate or undermine Nigeria's clean cooking transition?*. To address this, the empirical findings presented in Figures 3–8 offer valuable insights into the impact of governance infrastructure on clean cooking adoption across different quantiles, indicating that the Control of Corruption, Regulatory Quality, Rule of Law, and Voice & Accountability consistently exhibit a positive influence on both rural (RU) and urban (UF) access to clean cooking fuels and technologies. Notably, the effects are more pronounced at higher quantiles, suggesting that governance improvements have a greater impact in areas where clean cooking adoption is relatively high. The enhancing effect of corruption control is especially important in the context of Nigeria where misuse of public resources and secretive procurement practices have over the years impeded the success of energy-financed interventions. This conclusion aligns with the outcome of Adjei-Mantey, Kwakwa, and Ankrah (2025) in Africa, documenting that corruption control increases clean cooking transition in Africa. Enhancing anti-corruption mechanisms will likely improve the allocation and utilisation of public funds set aside for clean cooking initiatives, thereby accelerating clean energy transition. Likewise, improvements in the regulatory quality and rule of law is essential for the formulation of stable policy framework where the participation of the private sector, energy pricing and safety standards can be more implemented effectively and these factors are essential in shifting to sustainable cooking solutions. The enhancing influence of these variables on clean cooking aligns with these studies (Acheampong, Opoku, and Dogah 2023; Kwakwa 2024; Murshed 2023) while disagreeing with Acheampong (2023) and Shittu, Latiff, and Baharudin (2024).

At the lower quantiles, where Political Stability and Absence of Violence/Terrorism and Government Effectiveness are notably deficient, access to clean cooking remains both limited and erratic. In such institutional environments, the marginal impact of governance enhancements is markedly subdued. This pattern implies that in contexts characterised by fragile governance foundations, incremental institutional reforms are insufficient to yield significant improvements in clean cooking access. Conversely, in areas with stronger governance structures, further improvements significantly enhanced access to clean cooking technologies, likely due to more efficient policy implementation, better resource allocation, and increased public trust in government initiatives. These findings align with the diffusion of innovation framework, which posits that technological adoption spreads more effectively in environments where institutional support fosters perceived benefits, trialability, and observability. Robust governance structures are likely to contribute to expanding public awareness of clean cooking benefits through demonstration initiatives and policy-driven campaigns, thereby accelerating adoption rates (Katutsi et al. 2023; Lakum and Kumar 2024; Vatamanu and Zugravu 2023; Wang et al. 2022). Additionally, the results suggest potential threshold effects, wherein governance reforms may require a critical level of institutional strength before their impact on clean cooking adoption becomes substantial, aliging with rising empirical evidence, as seen in the case of (Acheampong, Opoku, and Dogah 2023; Kar and Swain 2023; Murshed 2023). This implies that targeted interventions should prioritise foundational governance improvements in lower-quantile areas before expecting significant shifts in clean cooking adoption.

Another crux of this study is ascertaining whether public debt stock (domestic and external) promotes or impedes the clean cooking transition in Nigeria. To address this, the empirical findings presented in Figures 9 and 10 offer valuable insights into the impact of public debt on clean cooking adoption across different quantiles. The quantile regression results indicate a minimal impact at lower quantiles, suggesting that affordability constraints could hinder the transition to clean fuels (Seriño 2017; Śmiech, Karpinska, and Bouzarovski 2025). This finding aligns with debt overhang theory, which posits that rising debt levels can hinder economic progress and investment (Onuoha et al. 2023a). Intuitively, increased debt burdens may create economic instability and reduce both private and public investments, potentially limiting the financial resources available for sustainable cooking initiatives (Dimnwobi et al. 2023b). This conclusion is consistent with the growing body of empirical evidence, as demonstrated in studies by Onuoha et al. (2023b), Auteri et al. (2024), Wang et al. (2021), Hashemizadeh, Bui, and Kongbuamai (2021), and Jabari, Aga, and Samour (2022). However, beyond the 0.4 quantile, as domestic debt levels increase, households appear to gain better access to financial resources, thereby enabling them to adopt cleaner cooking fuels such as LPG, which is also consistent with existing studies.

Furthermore, urban households generally exhibit higher adoption rates of clean cooking fuels because of their better infrastructure and higher income levels (Lokonon 2020; Pye et al. 2020). The minimal impact observed at lower quantiles indicates that at lower debt levels, urban households already possess sufficient financial resources to afford clean fuels. However, as the quantile level increases, the effect of domestic debt becomes more pronounced, peaking around the 0.9 quantile. This suggests that higher domestic debt levels further strengthen urban households' capacity to transition to cleaner cooking fuels, possibly due to improved financial stability and easier access to credit (see Oyeniran, Omojolaibi, and Alasinrin 2025). These findings highlight the critical role of financial (debt) policies and urban energy infrastructure development in facilitating the transition to clean cooking fuels across various income groups (Amu et al. 2025). They align with Keynesian theory, which suggests that government expenditure can stimulate economic growth even if it leads to increased public borrowing (Nwokoye et al. 2024). Moreover, this evidence is consistent with the existing literature that emphasises the importance of credit availability in driving clean cooking energy adoption in rural households (Farooq et al. 2022; Florea et al. 2021; Okere et al. 2023b; Onuoha et al. 2023a). The observed pattern suggests that targeted financial interventions such as structured public debt programmes could play a pivotal role in enhancing clean energy adoption in these areas.

5. Concluding remarks and policy directions

5.1. Conclusion

The current global drive towards minimising or eradicating unsustainable cooking methods owing to their harsh environmental, economic, and health effects is gaining momentum. Advancing the successful transition to clean cooking necessitates strategic debt management and effective governance. However, there is a paucity of studies examining the combined influence of governance quality and public borrowing on facilitating clean cooking technology usage. Hence, this study employs the Quantile-on-quantile method to assess the impact of governance and public debt on the uptake of clean cooking technologies in Nigeria from 2000Q1 to 2022Q4. The findings suggest that control of corruption, regulatory quality, rule of law, voice, and accountability consistently have a positive impact on access to clean cooking fuels and technologies in both rural and urban areas, with stronger effects observed at higher quantiles. Conversely, at lower quantiles, the influence of political stability and the absence of violence/terrorism, as well as government effectiveness, is relatively weak, reflecting persistent limitations and volatility in clean cooking access. Additionally, public debt has a negligible effect at lower quantiles, implying that when debt levels are low, governments' ability to invest in sustainable energy infrastructure and provide subsidies for clean energy uptake is limited. However, at higher quantiles, as public debt increases, the government can sufficiently fund sustainable energy initiatives and spur a transition to clean cooking in both urban and rural settings.

5.2. Policy recommendations

Our study revealed a stronger impact of governance measures in higher quantiles. Hence, tailored policy actions should be directed toward increasing clean fuel accessibility, especially in areas where the likelihood of uptake is higher. The expansion of infrastructure funding is vital for enhancing clean cooking distribution facilities and guaranteeing dependable access to eco-cooking options. The study further noted that at the lower quantiles, political stability and government effectiveness had a weak influence on clean cooking transitions. Hence, we suggest that efforts should be directed toward streamlining bureaucratic procedures and improving the capacity of institutions for effective policy execution. Minimising terrorism and violence is also essential for creating a conducive environment for investments in sustainable energy networks, particularly in high-risk zones. There is also a need to strengthen public-private collaborations to galvanise resources, promote technological advancements, and establish accessible eco-friendly facilities for households. The enhancement of public consciousness regarding the economic, health, and ecological gains of sustainable cooking technologies can propel behavioural adjustments and boost adoption. There is also a need to introduce vigorous monitoring and evaluation strategies to monitor the influence of governance strategies in advancing sustainable cooking methods, guaranteeing regular policy improvements and sustainable progress.

Our study highlights that public debt has a negligible impact on sustainable cooking at lower quantiles, but at higher quantiles, debt spurs the transition to clean cooking in Nigeria. Hence, we suggest that decision-makers judiciously utilise debt financing to foster sustainable cooking adoption, especially focusing on households in the higher quantiles where the effects were discovered to be very significant. It is also essential that governments enforce a tailored strategy for debt application, prioritising improvements in infrastructure and subsidy initiatives for sustainable cooking endeavours in both rural and urban locations. Financial resources emanating from debt should be directed into instituting strong distribution systems and establishing financial inducements that make sustainable cooking methods more affordable and accessible for households in the higher quantiles, while concurrently formulating an alternative financing framework for low-income populations where debt-driven efforts have a minimal effect. Decision makers in Nigeria should also establish holistic monitoring and evaluation that monitors the efficacy of debt-financed sustainable energy initiatives, which will guarantee that borrowed resources attain optimal effects in expanding the uptake of clean cooking.

In conclusion, to attain SDG 7, the Nigerian policymakers have established numerous interventions. For instance, the National Clean Cooking Policy targets universal clean cooking access by 2030. Similarly, the nation's Energy Transition Plan (ETP) which was introduced in 2022, articulates a clear vision to cooking transition as one of the efforts towards attaining carbon neutrality by 2060, targeting roughly 30 million households. Besides, initiatives like Nigeria LPG Expansion Implementation Plan (NLEIP) and assistance from the Clean Cooking Alliance have boosted the adoption of LPG, while public-private collaborations under the Nigeria Electrification Project (NEP) have financed sustainable energy startups. In light of the study's outcome, we suggest that the nation fortify anti-corruption monitoring in sustainable energy financing, enhancing enforcement of safety and distribution regulations for LPG, and boosting public participation in energy planning. Given the minimal impact of debt in lower quantiles, fiscal allocations should prioritise equity-focused deployment, especially in underserved regions. Improved governance and strategic use of debt are key to delivering inclusive, sustainable clean cooking access nationwide.

5.3. Limitations and future directions

This study has several shortcomings that future research can explore. First, the outcome of this study is limited to Nigeria, a developing economy. This economy differs significantly from advanced economies. Hence, policymakers should be cautious in generalising the policy insights of this research to developed economies. Second, the study's data are contingent on time-series data; hence, we were unable to thoroughly understand these dynamics at the community or household level, which can be critical in determining clean cooking adoption. Given this, future research could adopt micro-level assessments, which may yield more detailed insights. Third, we focused on public borrowing and governance efficiency as the major drivers of clean cooking, and other variables such as technological innovation, financial development, female empowerment, and natural resources should be considered in future research. Finally, nonlinear analytical techniques are applied in the current study. Given that the present study is a pioneering effort to understand the combined influence of governance quality and debt stock on the clean cooking transition, future research should consider adopting linear estimation approaches. This will assist in ascertaining whether the outcome is sensitive to the analytical technique employed.

Note

1. On the right side of Quantile-on-Quantile method (shown using fig. b and d).

Author contributions

CRediT: **Stephen Kelechi Dimnwobi:** Data curation, Visualization, Writing – original draft, Writing – review & editing; **Kingsley Ikechukwu Okere:** Conceptualization, Formal analysis, Investigation, Methodology; **Joan Nwamaka Ozoh:** Supervision, Validation, Visualization, Writing – review & editing; **Onyekachukwu Ernest Ebenebe:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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Data availability statement

Data available on request from the authors.

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Appendices

Appendix 1: Variable description

Variables	Description	Sources
External debt	Nigeria's Public External Debt Outstanding (₦' Billion)	Central Bank of Nigeria Statistical Bulletin
Domestic debt	Domestic Debt Outstanding (₦' Billion)	Central Bank of Nigeria Statistical Bulletin
Control of Corruption	Control of Corruption Index	World Governance Indicator database
Government Effectiveness	Government Effectiveness Index	World Governance Indicator database
Political Stability and Absence of Violence/Terrorism	Political Stability and Absence of Violence/Terrorism Index	World Governance Indicator database
Regulatory quality	Regulatory quality Index	World Governance Indicator database
Rule of Law	Rule of law Index	World Governance Indicator database
Voice & Accountability	Voice & Accountability Index	World Governance Indicator database
Urban clean cooking	Access to clean fuels and technologies for cooking, urban (% of urban population)	World Development Indicator database
Rural clean cooking	Access to clean fuels and technologies for cooking, rural (% of rural population)	World Development Indicator database

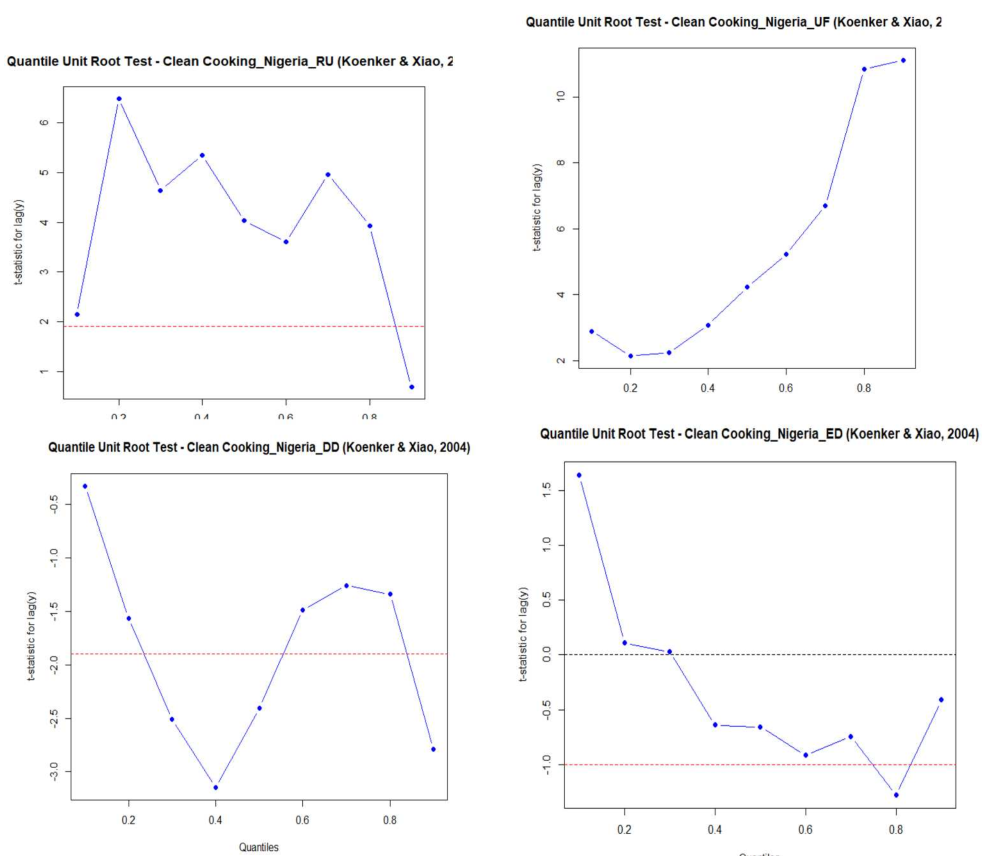

Figure A1. Source: Excerpt from R Studio.

Appendix 2. Quantile unit-Root estimates

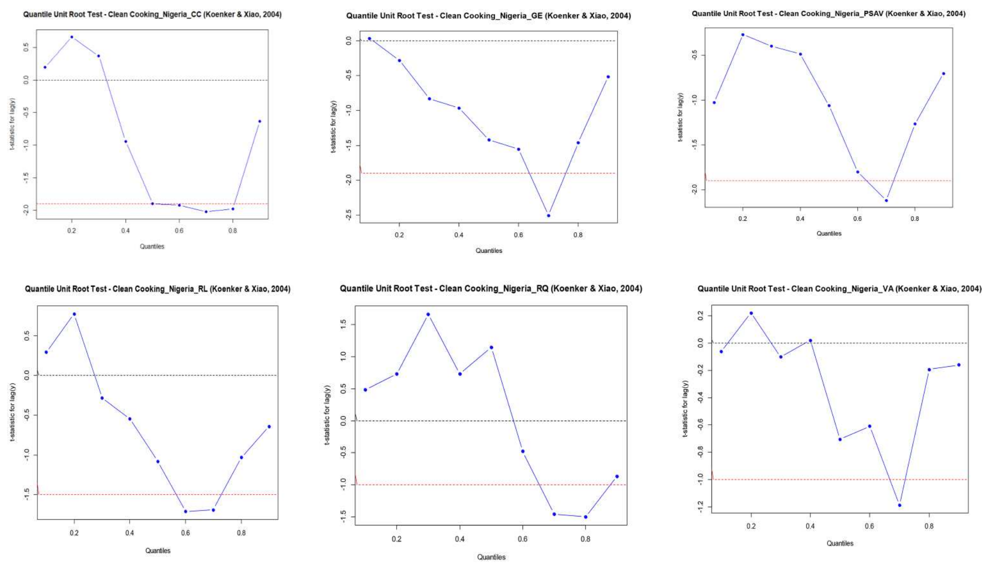

Figure A2. Source: Excerpt from R Studio.

Appendix 3. Graphical representation of QARDL

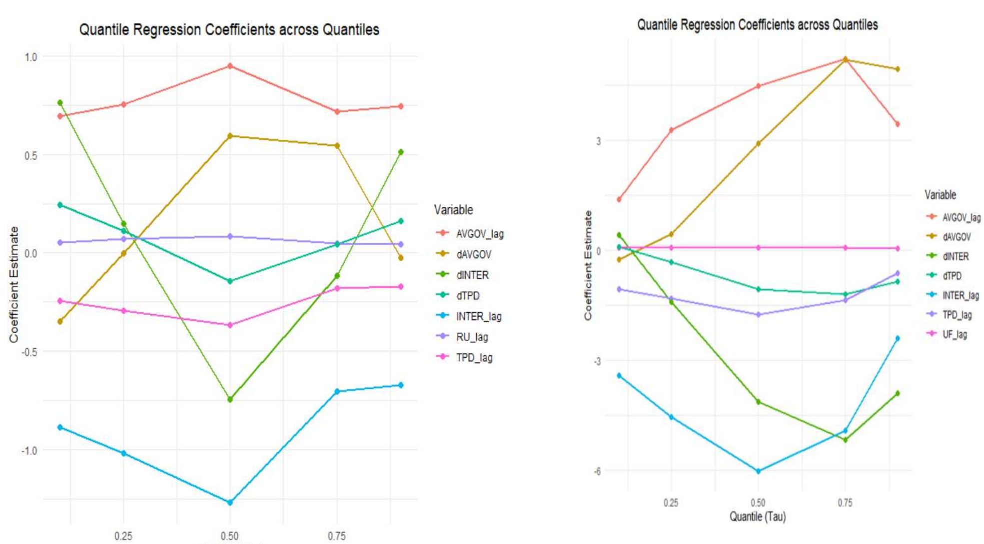

Figure A3. Source: Excerpt from R Studio.