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HETEROGENEOUS DETERMINANTS OF ENVIRONMENTAL SUSTAINABILITY: ASSESSING THE ROLES OF ENERGY CONSUMPTION, ECONOMIC GROWTH, AND FINANCIAL DEVELOPMENT

ABSTRACT: *This study offers unique insights into the heterogeneous influence of energy consumption, economic growth, and financial development on environmental sustainability in Sub-Saharan African (SSA) countries. Basically, the scarcity of evidence on this issue, especially in the context of SSA, motivates this new assessment. Thus, on the basis of the annual panel series for 22 SSA countries over the period 1999–2019, the novel quantile-based method of moments (MM-QR), and system-generalisation method of moments (sysGMM) provide the following results. First, financial development significantly degrades the region's environmental quality. Second, energy utilisation provides varying significant increasing effects. Whereas it largely increases carbon emissions at the upper quantiles, the influence at the middle and low quantiles is inconsequential. This highlights the fact that high levels of energy use in the region significantly increase carbon emissions, which in turn reduces the region's environmental sustainability. Third, the empirical result confirms the inverted U-form hypothesis in the region. Policy options to enhance and maintain sustainable growth in the region without compromising environmental quality have been highlighted.*

KEY WORDS: *environmental sustainability, economic growth, financial development, energy consumption, MM-QR, SSA*

JEL CLASSIFICATION: Q4, Q5, O4

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1. INTRODUCTION

The determination to comprehend, adapt, project, and streamline the main economic and noneconomic components impacting climate change has recently taken centre stage in world discussions. In particular, the United Nations espoused Sustainable Development Goals (SDGs) in 2015, with rigorous frameworks to guarantee that the world is more flourishing, more environmentally friendly, and inclusive by the year 2030. The SDGs' 11th, 12th, and 13th targets, respectively, delineated plans to ensure worldwide ecologically sound communities and cities, sustainable production and consumption structures, and environmentally conscious ecological actions. Furthermore, the Paris Convention in 2015 and the Intergovernmental Panel on Climate Change (IPCC) in 2018 recommended comprehensive blueprints for combating climate change and ensuring the development of less polluted environments worldwide. Additionally, the remarkable Paris conference (COP21) proposed well-thought policy targets, such as keeping the global temperature within 2°C above preindustrial levels while aiming for a further drop in the world temperature to at least 1.5°C. Regardless of how optimistic these global designs are, the bigger challenge is to properly pinpoint the elements driving climatic changes and the pathways on which they enter ecological systems and to ensure environmental sustainability. In particular, a number of variables, including economic growth (Shahbaz et al., 2014; Ali et al., 2016; Arshad et al., 2020; Rafindadi & Usman, 2019;Mesagan & Olunkwa, 2022; Osuntuyi & Lean, 2022; Akadiri et al., 2022), population (Opuala et al., 2022), energy use (Mohiuddin et al., 2016; Asumadu-Sarkodie & Owusu, 2016; Shahbaz et al., 2014; Rafindadi, 2016; Rafindadi & Usman, 2019; Adebayo et al., 2022; Opuala et al., 2022), exhaustion of natural resources (Dingru et al., 2023), financial development (Musah et al., 2022; Boutafeh & Saadaoui, 2020; Ye et al., 2020; Nwani & Omoke, 2020; Uche & Effiom, 2021, Anochiwa et al., 2022), urban sprawl (Opuala et al., 2022), structural transformations, technological advancements (Ahmed & Le, 2021), foreign direct investments (Opuala, et al., 2022), migration, institutions, and remittance inflows (Brown et al., 2020; Yang et al., 2021; Ahmad et al., 2022; Nwani et al., 2022; Uche, 2022) have been identified as potential determinants of environmental degradation.

Theoretically. the increased exploitation of petroleum-based energy sources as a significant component of energy resource availability, amongst other reasons, has been directly related to the increasing carbon dioxide emissions, which is seen as a major determinant of environmental sustainability (Owusu & Asumadu-Sarkodie, 2016; Owusu, et al., 2016). Furthermore, the momentous role of financial development (FD) in driving economic growth has been established (Levine et al., 2000; Levine, 2005), although some researchers believe that financial development can only strike a win-win balance between economic growth and environmental sustainability (M. Kahn et al., 2022); yet others argue that it is the backbone of economic growth because an organised and functional financial sector can provide economic stability (Odionye & Okorontah, 2014; Katircioglu & Taspinar, 2017). However, financial development is accompanied by an increase in energy consumption, which obviously leads to undesirable environmental degradation. The sudden rise in CO_2 emissions has been attributed to the increase in the production and consumption rate of industrially manufactured goods enhanced by financial development in the developed and developing countries. Many countries, especially developing ones, including African countries, have neglected the adverse environmental effects of CO_2 emissions in order to promote economic growth (Nwani et al., 2022).

Although the detrimental environmental effect of the use of energy is a worldwide concern, tackling the menace is critical in the context of CO_2 emissions because the African continent is reported to be at higher risk of the consequences of environmental degradation with very little adaptation capacity (International Energy Agency [IEA], 2019; United Nations Environment Programme, [UNEP], 2020). Considering the adaptability issues, and the importance attached to improving quality of life and also maintaining environmental quality, it is imperative in the context of SSA to explore what drives environmental sustainability. Furthermore, the trajectory of carbon emissions in Sub-Saharan Africa has increased significantly in the previous few decades. World Bank data (2021) indicate that carbon emissions in SSA increased by more than 380% between 1960 and 1990. They increased by 26.1% between 1990 and 2000, rising from 1,213,589.1 kt to 1,529,884.4 kt. Between 2000 and 2020, they climbed by around 47.6%, from 1,529,884.4 kt to 2,258,595.5 kt. This shows the substantial upsurge in carbon emissions in the region, given that the region's energy use is among the lowest in comparison to other regions.

According to WMO (2022), the region's temperature, as an indication of elevated carbon emissions, rose faster than the rest of the world in 2021. WMO (2022) indicates that between 1991 and 2021 Africa continued warming, exhibiting a mean rate of change of roughly +0.3 °C/decade, compared to +0.2 °C/decade between 1961 and 1990, 0.04 °C/decade between 1931 and 1960, and +0.08 °C/decade between 1901 and 1930. Africa has warmed faster than the rest of the world (WMO, 2022). According to the IPCC AR6, rising average temperature trends across Africa are caused by human-caused climate change. Between 1901-1930, and 1991-2021, all six African sub-regions witnessed a rising trend in temperatures.

Not with standing the increasing number of studies on drivers of ecological systems, there is still a dearth of studies focusing on the heterogeneous influence of energy use, financial development, and economic growth on environmental sustainability in the context of Sub-Saharan African countries. The existing studies on SSA, which include Opuala et al. (2022), Uche and Effiom (2021), Nwani et al. (2022), and Dingru et al. (2023), did not consider the heterogeneous determination of environmental sustainability, except Anochiwa et al. (2022), which examined the distributional link between financial deepening and CO_2 emissions. While Nwani, et al. (2022) focused on the relationship between remittances and CO_2 emissions in SSA, Dingru, et al (2023) centered on the renewable energy influence of trade and natural resources in SSA. Opuala et al. (2022) examined the interconnection between financial development, energy use, and environmental quality in the West African region. Furthermore, extant studies reveal two exceptional features in the literature on the connection between environmental quality and growth. Some studies found a bidirectional link between the series of data (see Rafindadi, 2016; Rafindadi & Usman, 2019; Mesagan et al., 2022; Musibua et al., 2021; Mung et al., 2021). Moreover, the impact on environmental quality can be influenced by the size of the growth rate, in line with the environmental Kuznets curve (EKC), as well as the developmental stage of a nation in line with the environmental transition (ET) theory. The environmental transition theory posits that the environmental challenge changes as the developmental stage of a city changes (McGranahan et al., 2001; Shahbaz, et al., 2014; Rafindadi, 2016; Rafindadi & Usman, 2019). The above strands of empirical evidence point to the econometric issues of endogeneity and heterogeneity on the interaction between the series of data. So far, reliance on empirical evidence to resolve the heterogeneous determinants of environmental sustainability issues has yet to yield the much-needed result, thus leaving the empirical question open for further investigation.

This study contributes to the existing energy-environmental economics literature in the following ways: first, it utilises the novel quantile-based GMM (MM-QR) approach developed by Machado and Silver (2019) to assess the heterogeneous determinants of environmental sustainability in 22 selected countries in SSA; second, it extends the study of Anochiwa et al. (2022) by using total CO_2 emissions, rather than consumption-based emissions; third, while Anochiwa et al. (2022) was limited to 19 countries in SSA, this study extends the cross-sectional units to 22 SSA nations, with the selection of nations based on data availability; fourth, a newly modified version of GMM that permits nonlinear moments and improves efficiency and robustness of the estimates as suggested by Kripfganz (2020) was utilised for robustness estimates.

In the light of the foregoing, the study employed the novel MM-QR with the fixed effects method, which takes into account the econometric issues of heterogeneity and endogeneity, to estimate the size-based influence of the listed explanatory variables on environmental sustainability in SSA. In addition to the introductory section, the remaining parts of the study are organised as follows: section two reviews the literature, section three discusses the methodological framework, section four discusses the empirical results, and section five concludes with policy implications and recommendations.

2. LITERATURE REVIEW

2.1 Theoretical literature

Some theories have linked environmental sustainability with some economic and non-economic factors such as economic growth, energy consumption, financial development, urbanisation, and others, which in turn demands appropriate policies and their effective implementation to enhance a sustainable environment. The two main theories guiding this study are the environmental Kuznets curve and the environmental transition theory (McGranahan et al., 1996, 2001). The EKC postulates that economic growth and development initially harm the environment, but after some progressive level of economic growth, there is an improvement in the relationship between society and its environment which results in a reduction in societal environmental degradation. The EKC hypothesises that production activities and economic growth results in persistent environmental pollution which is detrimental to environmental sustainability. Structural transformations to facilitate economic growth increase carbon emissions and green development is not adequate to offset the overall environmental damage. There is a rise in demand for energy and massive use of natural resources as nations seek higher growth and development. Consequently, there is excess waste generation, carbon dioxide emissions, and so on, resulting in environmental degradation (Iheonu et al, 2022). The EKC is generally represented as an inverted U-shape curve. On the other hand, the ET theory posits that there exist diverse environmental issues linked with progress that do not follow the EKC trend (McGranahan et al., 1996, 2001). McGranahan et al. (2001) show that as cities get wealthier, their environmental effects move from being a localised menace to a worldwide ecosystem problem. The ecological menace changes from the rural-level problems of water accessibility and sanitation problems to urban problems of air and water pollution as certain areas grow from rural to urban areas. For cities grappling with "green" concerns, the most substantial ecological effects of urban-based activities are regional, if not global (e.g., greenhouse gas, acid rain, and ozone depleting chemical emissions). The theory states that nations experience a number of environmental problems as they grow and develop, and such growth and development are mainly functions of industrialisation, which demands higher energy consumption and financial development, resulting in higher CO_2 emissions (Iheonu et al., 2022) Thus, the scale of the ecological problem is development-dependent.

2.2 Empirical review

Many researchers in developed and emerging nations of Asia have conducted empirical studies linking financial development, energy utilisation, economic growth, and other economic and non-economic variables with environmental sustainability, while very few studies on countries of the African continent exist. Amongst the prior studies on African countries are, notably, Shahbaz et al. (2014) on Tunisia, Asongu et al. (2019) for 13 African countries, Rafindadi and Usman (2019) for South Africa, Rafindadi (2016) and Uche and Effiom (2021) on Nigeria, Musah et al. (2022) on selected countries of West Africa, Boutafeh and

Saadaoui (2020) on 22 African countries, and Mesagan and Olunkwa (2022) on 18 African countries.

Shahbaz et al. (2014) and Rafindadi and Usman (2019) adopted the vector error correction model (VECM) and the causality estimation technique to evaluate the EKC supposition in Tunisia and South Africa, respectively. Both studies support the EKC view for the investigated nations. While the study of Rafindadi and Usman (2019) indicates an inverse impact of globalisation on environmental quality, Shahbaz et al. (2014) favours trade openness as a co-driver of environmental quality. Rafindadi and Usman (2019) also detected a one-way direction of influence of energy utilisation on environmental sustainability. Similarly, in the context of Nigeria, Rafindadi (2016) examined the effect of economic growth and financial development on carbon emissions. The study adopted diverse dynamic estimation techniques such as autoregressive distributed lag model (ARDL), VECM, and causality approaches in its data analysis. The study's outcome indicates that financial development significantly increases energy utilisation but improves environmental quality, while economic growth reduces energy utilisation but worsens environmental quality in Nigeria. A similar study was conducted by Asongu et al. (2019) in selected African countries using a pooled mean group (PMG) version of ARDL and the study's result confirms the environmental Kuznets curve postulation.

Anochiwa et al. (2022) focused on the distributional influence of financial development on consumption-based carbon emissions in 19 selected SSA countries. The study employed the quantile-based version of the generalised method of moments analytical approach in its estimation. The study's outcome indicates that financial development significantly worsens the region's environmental sustainability through CO_2 emissions. In addition, it refutes the EKC hypothesis. Similarly, S. Khan et al. (2021) used dynamic econometrics estimation techniques in the context of 184 nations and observed that financial deepening significantly worsens the environmental quality of the selected nations, while energy utilisation significantly increases CDE and hence leads to a deterioration of environmental sustainability. In contrast, Omoke et al. (2020), in the case of Nigeria, examined the symmetric and asymmetric reaction of environmental deterioration to positive and negative changes in financial development. The study employed an ARDL framework and its nonlinear version in its data analysis and observed a short-term asymmetric link between the investigated series. The study also observed a direct link between elevated financial development and environmental deterioration through increased carbon emissions in Nigeria.

Musah et al. (2022) utilised the cross-sectional autoregressive distributed lag (CS–ARDL), cross-sectional augmented error correction (CAEC), as well as the cross-sectional augmented distributed lag (CS–DL) methods of estimation to explore the relationship between financial development and environmental sustainability in West Africa. The study's outcome shows that financial development is detrimental to environmental quality in West Africa through increased carbon emissions. Researchers with the same result are Boutafeh and Saadaoui (2020), who adopted the ARDL–PMG estimation method in 22 African countries, Ye et al. (2021) in Malaysia, Nwani and Omoke (2020) in Brazil, and Ahmed et al. (2021) in Japan, all with the ARDL technique.

However, Boutafeh and Saadaoui (2020) as well as Mesagan and Olunkwa (2022), using ARDL–PMG and pooled mean group estimation methods in 22 and 18 African countries, respectively, examined the long-term and short-term effects of financial development on environmental sustainability, and their findings show that financial development has a long-term inverse influence on environmental sustainability. However, it indicates that financial development in the short run enhances environmental sustainability.

A few studies have looked at how energy utilisation influences environmental sustainability. Mesagan and Olunkwa (2022) examined how energy consumption affects environmental pollution in 18 African countries using the PMG estimation method while Osuntuyi and Lean (2022) used ARDL–PMG and heterogeneous causality test estimation methods to investigate the effect of energy consumption on environmental degradation in 92 countries. Their empirical results indicate that energy consumption has a negative effect on environmental pollution and environmental degradation, respectively, in the short run, whereas Mesagan and Olunkwa (2022) found that environmental pollution was positively and significantly affected by energy consumption in the long run. Similarly, Shahbaz et al. (2013) used the VECM estimation technique to obtain the same result in the South African economy using CO_2 emissions as a proxy for environmental sustainability.

Omojolaibi (2010) determined how economic growth affects environmental sustainability in West Africa. He used carbon emissions as a proxy for environmental sustainability and the result from his panel data estimation research indicates that economic growth negatively affects environmental sustainability. The study suggests that governments of West African countries should adopt energy conservation policies in the economic production process to avoid environmental degradation. S. Khan et al. (2021), using an ARDL estimator, obtained a similar result in Pakistan: economic growth increases carbon emissions, which is detrimental to environmental sustainability. In addition, the outcome of Marques et al. (2018), using dynamic ordinary least square (OLS) and an autoregressive distributed lag model, affirms that economic growth had a significant negative long-run effect on carbon emissions in Australia. Farhani et al. (2014) tested the environmental Kuznets curve hypothesis in ten North African and Middle East countries using a panel data method. The result indicates that economic growth and human development negatively affect environmental sustainability. Ondaye et al. (2021) studied the influence of economic growth on CO_2 emissions in the Republic of Congo from 1980 to 2015 using ARDL modelling and showed that economic growth has no significant effect on CO_2 emissions in the period under review. Similarly, Shahbaz et al. (2014) utilised the VECM estimation technique to investigate the effect of energy consumption and economic growth on environmental sustainability in the Tunisian economy and demonstrated that CO_2 emissions increased as a result of an increase in energy consumption and economic growth.

Mesagan et al. (2022) studied the effect of carbon emissions and energy consumption on economic growth in West African countries using Granger causality and full maximum OLS estimation techniques. Their findings indicate that increased energy consumption and carbon emissions enhanced economic growth in West Africa. A unidirectional causal relationship from environmental pollution to energy consumption as well as bidirectional causality between carbon emissions and output growth were found in Ghana while, economic growth Granger causes carbon emissions in Gambia. Their study differs from our own in the sense that it looked at the effect of carbon emissions (a proxy for environmental sustainability) and energy consumption on economic growth while our work will look at how energy consumption and economic growth affect environmental sustainability. Similarly, Musibua et al. (2021) empirically investigated the effect of environmental performance on economic growth of West African. They used two stage least square (2SLS) and moment quantile research methods to find that environmental performance positively affects economic growth in ECOWAS nations.

Our study departs from existing studies by adopting the novel quantile-based GMM (MM-QR) approach developed by Machado and Silva (2019) to assess the heterogeneous determinants of environmental sustainability in 22 selected SSA countries. Closest to this study in terms of approach is that of Anochiwa et al. (2022), which employed MM-QR to examine the connection between financial development and consumption-based CO_2 emissions in 19 SSA nations. Our study extends Anochiwa et al. (2022) by examining the heterogeneous drivers of environmental sustainability, the roles of economic growth, financial development, and energy use, utilising production-based carbon emissions as well as extending the cross-sectional units to 22 nations in SSA, carefully selected on the basis of data availability. In addition, we used two-step GMM, as suggested by Blundell and Bond (1998), and its newly modified version, which permits nonlinear moments and improves the efficiency and robustness of the estimates, as suggested by Kripfganz (2020).

3. METHODOLOGY

3.1 Data description

To uncover the intricacies surrounding the interactions of the relationship under study, the investigation harvests annual balanced panel series covering the period 1999–2019 drawn from 22 selected SSA countries. The choice of the selected countries was based on data availability. Furthermore, the choice of techniques is predicated on a short-panel framework with a larger cross-sectional (N) dimension and a smaller time (T) dimension (N=22 >T=21). Additionally, due to the study's objectives of assessing the heterogeneous influence of energy consumption, economic growth, and financial development on environmental quality, relevant macroeconomic series were extracted from the World Bank's data repository for empirical estimations. Table 1 provides a detailed explanation of the composition of these identified panel series.

Table 1: Data descriptions

Series	Notation	Unit of measurement	Source
CO2 Emissions	Cdm	CO2 emissions, (metric tons per capita)	WDI
Energy Consumption	Erc	Energy used (kg of oil equivalent per capita)	WDI
Gross Domestic Product	Gdp	GDP at market prices (current USD)	WDI
Growth Rate of GDP per capita	GrGDP	The annual percentage growth rate of GDP per capita based on constant USD	WDI
Financial Development	Fdt	Domestic credit to private sector (% GDP)	WDI
Population	Ppu	Population (total)	WDI
Urban Population	Ubn	Urban population (% of total population)	WDI
Selected SSA countries: Benin, Botswana, Cameroon, Côte d'Ivoire, DR Congo, Congo Republic, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, Tanzania, Togo, Zambia, and Zimbabwe			

Note: WDI denotes World Development Indicators, World Bank data repository (WDI, 2022).

3.2 Model specification

Consistent with the Kuznets environmental curve (EKC) hypothesis and in line with relevant prior studies (Osuntuyi & Lean, 2022; Mesagan & Olunkwa, 2022), our investigation considers a dynamic panel estimation process, namely MM-QR, to evaluate the heterogeneous influences of energy consumption, economic growth, financial development, and other control variables on environmental quality in SSA countries. The inclusion of the control variables is premised on their critical roles in affecting environmental sustainability, which is consistent with the relevant prior studies (Shahbaz et al., 2014; Rafindadi, 2016; Rafindadi & Usman, 2019). Consequently, the following equation describes the model linking environmental quality with the explanatory variables.

$$lcdm_{it} = b_0 + b_1 lerc_{it} + b_2 lgdp_{it} + b_3 lgdp^2_{it} + b_4 lfdt_{it} + b_5 lppu_{it} + b_6 lubn_{it} + \varepsilon_{it} \quad (1)$$

In Equation 1, *lcdm, lerc, lgdp,* $lgdp^2$*, lfdt, lppu* and *lubn* represent the natural log of CO_2 emissions, energy consumption, gross domestic product, squared GDP, financial development, total population, and urban population, respectively. Two different measures of growth were used in the study, namely growth rate of GDP per capita (2010 constant USD) and GDP at market prices. The reason is to validate the result that was obtained using nominal GDP and to serve as a robustness check. Growth rate of GDP per capita has been widely used as a proxy for growth in environmental studies (Rafindadi, 2016; Rafindadi & Usman, 2019; S. Khan et al., 2021; Anochiwa et al., 2022). Additionally, the subscripts i and t denote the cross-sectional and time dimensions, respectively, while ε indicates the stochastic error component. Instructively, all the series used were transformed to natural logarithmic values essentially to minimise the chances of serial correlation and to allow for consistent estimates based on point elasticities.

3.3 Estimation techniques

Method of Moments Quantile Regression (MM-QR)

As highlighted earlier, the study utilised the newly introduced MM-QR panel in the evaluation of the interactions of the listed series on environmental sustainability in SSA. It is interesting to note that this procedure was performed primarily to generate novel perspectives and improve understanding of the heterogeneous influence of the listed series on environmental sustainability in SSA, given that such empirical accounts are uncommon in previous studies. Aside from the apparent, the choice of the MM-QR is also based on the significant characteristics of this recently suggested panel estimator. As a result, these benefits include its capacity to expose the implications of changes in variables on the response variable throughout a range of distributions in a more complete manner using moment (quantile regression via moments) stages (Machado & Silva, 2019). Moreover, while the approach is robust in the presence of heteroscedasticity and outliers, it also reveals distributional heterogeneity along the conditional distributions of the outcome variable (Bista & Khan, 2022). Remarkably, unlike previous convectional quantile regression approaches, the MM-QR method takes into account unique country-specific fixed effects that are resistant to incidental parameter challenges over its entire distribution (Bista &

Khan, 2022). In addition, the MM-QR, which can handle irregularly distributed data, is based on both location and scale effects. The baseline location-fixed effects quantile technique was inspired by Machado and Silva (2019) and several similar recent investigations (Adeleye et al., 2022; Boikos et al., 2022). This procedure is thus represented in Eqn. (2).

$$Q_{\Upsilon}(\tau \mid X_{it}) = (\alpha_i + \theta_i \delta_i) + X'_{it}\beta + K'_{it}\gamma\rho(\tau) \quad (2)$$

In Eqn. (2), $Q_{\Upsilon}(_{\tau} \mid X_{it})$ shows the conditional quantile distributions of the outcome variable, which is determined by the explanatory variables; X_{it} represents the vector of all the listed predicting variables; $\alpha_i(\tau) = \alpha_i + \theta_i \delta_i(\tau)$ represents the scalar coefficient of the $\tau - th$ quantile of the individual *i* specific fixed effects; K'_{it} describes the *K*-vector; $\rho(\tau)$ represents the $\tau - th$ quantile, which has been expressed through an optimisation process illustrated in Eq. (3).

$$\min_{\theta} \sum_i \sum_t \sigma_{\tau}(F_{it} - (\delta + K'_{it}\gamma)\theta) \quad (3)$$

where $\rho_{\tau}(A) = (\tau - 1)AI\{A \le 0\} + \tau AI(\{A > 0\})$ symbolises the quantile conditional check-function. Following Eqn 1, in specific form, the MM-QR is expressed as:

$$Qlcdm(\tau \mid X_{it}) = \beta_0 + \beta_1 lerc_{it} + \beta_2 \lg dp_{it} + \beta_3 \lg dp_{it}^2 + \beta_4 lfdt_{it} + \beta_5 lppu_{it} + \beta_6 \operatorname{lub} n_{it} + \varepsilon_{it} \quad (4)$$

The variables are defined as in Eqn 1.

System Generalized Methods of Moments (sysGMM)

As a robustness check, two-step GMM, as suggested by Blundell and Bond (1998), and its modified version that permits nonlinear moments (Ahn & Schmidt, 1995) and improves the efficiency and robustness of the estimates (Kripfganz, 2020) were used. Given the composition of the relevant panel series on the basis of which the estimated outcomes of this study are predicted, the method of moments (GMM) procedures and their related extensions are preferred. This choice of the GMM panel estimator is also premised on the fact that it remains the predominant technique in several studies with similar frameworks. It is worthwhile to highlight that, in contrast with the steps taken in the prior literature, the current investigation took advantage of both the linear and nonlinear variants of the system generalised methods of moments (*sys*GMM) techniques. Instructively, the choice of the GMM dynamic panel estimator introduced by Arellano and Bond (1991) and its extension by Arellano and Bover (1995) is justified in several respects. First, the study used a micro-dynamic panel framework where the number of the cross-sections surpasses the number of observations (N>T), which ultimately controls for dynamic panel bias (Bond, 2002; Omri, 2020; Roodman, 2009). Given the N>T framework, the precondition to adopt the GMM procedure is fulfilled. Second, the preference for the sysGMM is predicated on the fact that it controls for infinite sample bias more efficiently than the difference GMM (Baltagi, 2009). Likewise, the model produces more robust estimates; hence, it efficiently controls the endogeneity bias associated with such a dynamic panel framework. In addition, the sysGMM estimator also accounts for reverse causality and at the same time ensures that cross-sectional exigencies are not precluded in the regression (Khan & Ozturk, 2021). Additionally, unlike the estimates of related prior studies that emerged through the *xtabond2* Stata command, this study preferred the *xtdpdgmm* command that generates robust nonlinear estimates within the sysGMM process (Kripfganz, 2020). Furthermore, the *estat serial, (1/2)* and the *estat overid* commands were relied upon for Arellano–Bond's first-differenced residuals autocorrelation test and Sargan–Hansen's overidentifying restriction test, respectively.

4. RESULTS AND DISCUSSION

4.1 Descriptive statistics and correlation matrix

Empirical presentations often start with some rudimentary descriptive test that sets the way for more robust estimations. Therefore, summary statistics and correlation tests were applied to the necessary series for the purpose of this study. These tests, among other things, indicate the form of the distributions, the series' behavioural trends, as well as the strength of the relationships. Specifically, descriptive statistics provide information that highlights whether the series are typically distorted whereas the correlation matrix divulges any likely multicollinearity issues. Table 2, therefore, summarises the test results.

Table 2: Descriptive statistics and correlation matrix

	LCDM	LERC	LFDT	LGDP	GrGDP	$LGDP^2$	LPPU	LUBN
	Panel A: Descriptive Statistics							
Mean	-0.946	6.237	2.699	23.13	2.431	536.72	16.28	4.081
Maximum	2.149	8.048	5.076	27.07	12.41	732.73	19.01	14.65
Minimum	-3.429	4.728	-0.710	20.18	-9.421	407.17	13.91	2.627
Std. Dev.	1.404	0.669	0.957	1.283	2.872	60.65	1.331	2.305
Skewness	0.364	0.662	-0.148	0.758	0.632	0.953	-0.129	4.154
Kurtosis	2.316	3.708	4.404	3.980	3.104	4.307	2.098	18.91
Jarque–Bera	19.19**	43.44**	39.64**	62.76**	30.27**	102.9**	16.91**	620**
Probability	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Observations	462	462	462	462	462	462	462	462
	Panel B: Correlation Matrix							
LCDM	1							
LERC	0.699	1						
LFDT	0.603	0.545	1					
LGDP	0.117	0.457	0.262	1				
LGDPPC	0.245	0.356	0.123	0.345	1			
LGDP2	0.119	0.461	0.271	0.799	0.674	1		
LPPU	-0.586	-0.148	-0.192	0.636	0.234	0.637	1	
LUBN	0.283	0.145	0.216	-0.080	-0.211	-0.084	-0.373	1

Note: ** and * depict statistical significance at the 1% and 5% significance levels, respectively

Table 2 demonstrates that the series deviates from the normal distribution on the basis that the Jarque–Bera statistics are significant. It is worth noting that these outcomes justify the application of GMM approach within the quantile framework, which is capable of producing robust estimates amidst an abnormal distribution (Koenker & Bassett, 1987; Ullah et al., 2022; Bista & Khan, 2022; Uche, Odionye & Ngepah, 2023; Uche et al., 2023; Odionye et al., 2023; Odionye, Ojiake & Uba, 2023; Odionye et al., 2024). The correlation matrix (Panel B) indicates the absence of multicollinearity as the correlation coefficients between the explanatory variables are less than 0.8.

4.2 The methods of moment quantile regression (MM-QR) estimates

As stated earlier, the MM-QR is the baseline estimation relied upon to explain the heterogeneous influence of energy consumption, economic growth, and financial development on environmental sustainability in SSA. Instructively, the relevant outcomes are summarised in Table 3 for brevity.

Based on the abridged outcomes in Table 3 (Panel A and B) generated from the MM-QR, it is important to emphasise that, among other interesting results, financial development (lfdp) largely increases carbon emissions in the SSA across all the quantiles. The outcome also demonstrates that the influence of financial development on environmental sustainability via CO_2 emissions increases heterogeneously along the upper quantile change. The results were not different when GDP per capita was used as a proxy for economic growth (Panel B). What this means is that financial development significantly worsens region environmental sustainability; as the region's financial sector deepens, it increases CO_2 emissions, and thereby enervates the environmental quality in the SSA region. This outcome aligns with the results of Musah et al. (2022) for West African countries, Boutafeh and Saadaoui (2020) for 18 selected African countries, Ye et al. (2020) for Malaysia, Nwani and Omoke (2020) for Brazil, and Ahmed et al. (2021) but contradicts the finding of Mesagan and Olunkwa (2022) for 18 African countries.

Pertaining to energy consumption (lerc), the computations demonstrate that its influence is heterogeneous in both models (Panels A and B). Categorically, with regard to location and scale, as well as at the upper quantiles (qtile_70–qtile_90), energy consumption provides varying significant increasing effects. Whereas at the upper quantiles (qtile_70–qtile_90) it largely increases carbon emissions by 0.269%, 0.288%, and 0.298%, respectively, at the middle and low quantiles (qtile_10–qtile_60) the influence is inconsequential. This highlights the fact that the high level of energy used in the region significantly increases carbon emissions, which in turn reduces the region's environmental sustainability. The implication of this outcome is that high-energy-consuming nations experience high carbon emissions, hence increasing the environmental sustainability problem. This corroborates the results of Rafindadi and Usman (2019) for South Africa, Mohiuddin et al. (2016) for Pakistan, Asumadu-Sarkodie and Owusu (2016) for Ghana, Shahbaz et al. (2014) for Tunisia, and Rafindadi (2016) for Nigeria.

Table 3. Estimates of MM-QR

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
VARIABLES	Location	Scale	qtile_10	qtile_20	qtile_30	qtile_40	qtile_50	qtile_60	qtile_70	qtile_80	qtile_90
Panel A: GDP at market value											
Lerc	0.240**	0.113**	0.170	0.195	0.213	0.227	0.242	0.255	0.269***	0.288**	0.298**
	(0.081)	(0.043)	(0.207)	(0.163)	(0.154)	(0.162)	(0.185)	(0.212)	(0.046)	(0.097)	(0.116)
Lfdt	0.194***	0.090**	0.129**	0.152***	0.169***	0.182***	0.197***	0.209***	0.222***	0.239***	0.258**
	(0.0546)	(0.0433)	(0.0625)	(0.0493)	(0.0465)	(0.0489)	(0.0559)	(0.0640)	(0.0742)	(0.0893)	(0.107)
Lgdp	0.143**	0.0611	0.0437	0.0795	0.105**	0.124**	0.147**	0.165**	0.184**	0.211**	0.239**
	(0.0616)	(0.0489)	(0.0705)	(0.0557)	(0.0525)	(0.0512)	(0.0631)	(0.0721)	(0.0835)	(0.101)	(0.120)
lgdp2	-0.103**	0.107**	-0.0037	-0.0015	-0.105	0.124**	0.147**	-0.44***	-0.452**	-0.47***	-0.46***
	(0.0416)	(0.0409)	(0.0405)	(0.0557)	(0.352)	(0.0552)	(0.0631)	(0.1101)	(0.160)	(0.101)	(0.096)
Lubn	-0.126	0.0456	-0.200	-0.173	-0.154	-0.139	-0.123	-0.109	-0.0944	-0.0748	-0.0535
	(0.302)	(0.240)	(0.345)	(0.273)	(0.257)	(0.271)	(0.310)	(0.355)	(0.412)	(0.497)	(0.595)
Lppu	-0.0431	-0.294	0.434	0.262	0.141	0.0461	-0.0614	-0.150	-0.244	-0.370	-0.507
	(0.267)	(0.212)	(0.306)	(0.242)	(0.228)	(0.239)	(0.274)	(0.313)	(0.362)	(0.436)	(0.522)
Constant	-5.055	2.963	-9.860***	-8.126***	-6.906**	-5.953**	-4.870	-3.981	-3.035	-1.763	-0.381
	(3.278)	(2.602)	(3.751)	(2.964)	(2.793)	(2.938)	(3.357)	(3.840)	(4.448)	(5.358)	(6.417)
Observations	462	462	462	462	462	462	462	462	462	462	462
Fixed effect	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Panel B: Growth rate of GDP per capita

Lerc	0.242**	0.116**	0.172	0.191	0.196	0.213	0.222	0.245	0.25***	0.291**	0.296**
	(0.091)	(0.043)	(0.207)	(0.163)	(0.172)	(0.222)	(0.195)	(0.212)	(0.046)	(0.097)	(0.116)
Lfdt	0.189**	0.092**	0.109**	0.121***	0.15***	0.18***	0.19***	0.19***	0.201**	0.22***	0.23**
	(0.0646)	(0.0411)	(0.0425)	(0.0421)	(0.037)	(0.046)	(0.062)	(0.061)	(0.084)	(0.0793)	(0.101)
Lgdp	0.101**	0.06**	0.036	0.079**	0.085**	0.101**	0.106**	0.112**	0.112**	0.17***	0.19**
	(0.038)	(0.029)	(0.071)	(0.036)	(0.0325)	(0.041)	(0.041)	(0.0421)	(0.0435)	(0.044)	(0.042)
lgdp2	-0.11**	0.10**	-0.011	-0.015	-0.096	0.105**	-0.15**	-0.19**	-0.19**	-0.23**	-0.24**
	(0.039)	(0.044)	(0.041)	(0.036)	(0.052)	(0.035)	(0.061)	(0.060)	(0.060)	(0.06)	(0.077)
Lubn	-0.124	0.031	-0.181	-0.164	-0.167	-0.144	-0.133	-0.141	-0.195	-0.175	-0.153
	(0.302)	(0.240)	(0.421)	(0.273)	(0.117)	(0.171)	(0.271)	(0.312)	(0.251)	(0.217)	(0.495)
Lppu	-0.123	-0.164	0.401	0.311	0.141	0.0461	-0.0614	-0.150	-0.244	-0.370	-0.507
	(0.231)	(0.212)	(0.356)	(0.282)	(0.228)	(0.239)	(0.274)	(0.313)	(0.362)	(0.436)	(0.522)
Constant	-5.055	2.963	-9.86***	-8.13***	-6.91**	-5.94**	-4.82	-3.97	-3.03	-1.76	-0.381
	(3.278)	(2.602)	(3.751)	(2.964)	(2.793)	(2.938)	(3.357)	(3.840)	(4.448)	(5.358)	(6.417)
Observations	462	462	462	462	462	462	462	462	462	462	462
Fixed effect	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Regarding the economic growth variable (lgdp) and its square ($lgdp^2$), the results in Table 3 (panels A and B) confirm the inverted U-form hypothesis that at the initial developmental stage, elevated economic growth increases CO_2 emissions (degrades environmental quality) but at a later stage, after some progressive level of economic growth, there comes a relationship enhancement between society and its environment which results in a reduction in societal environmental degradation. This obvious outcome is exemplified by the positive and significant influence of lgdp on CO_2 with regard to location as well as at the middle and upper quantiles (qtile_30–qtile_90), while the location, scale, and various quantiles of $lgdp^2$ demonstrate the varying nature of the influence of the square of economic growth ($lgdp^2$), with negative coefficients at the 60^{th}, 70^{th}, 80^{th}, and 90^{th} quantiles. When the growth rate of GDP per capita was used as a proxy for growth (Panel B), the outcome further verifie the U-shape hypothesis as both the level and square of GDP are significant. These outcomes, irrespective of the measure of GDP utilised, align with those of Shahbaz et al. (2014) for Tunisia, Rafindadi (2016) for Nigeria, Mesagan and Olunkwa (2022) for selected African countries, S. Khan et al. (2021) for 184 selected, Marques et al. (2018) for Australia, Farhani et al. (2014), and Osuntuyi and Lean (2022) for 92 countries. Shahbaz et al. (2014) found that as the square of GDP reduces carbon emissions, GDP increases them. The result also indicates that population (lppu) and urbanisation (lubn) insignificantly affect environmental sustainability in the region.

Table 4: Impact of the explanatory variables on the environmental sustainability using the GMM approach

	GDP at Current Prices			Growth Rate of GDP per capita		
VARIABLES	**SGMM[1]**	**SGMM**	**DGMM**	**SGMM[1]**	**SGMM**	**DGMM**
Lcdm	0.634***	0.87***	0.755***	0.59***	0.731***	0.821***
	(0.1199)	(0.106)	(0.153)	(0.116)	(0.261)	(0.323)
Lerc	0.141**	0.25***	0.318*	0.111**	0.231***	0.256*
	(0.0673)	(0.087)	(0.168)	(0.0373)	(0.078)	(0.148)
Lfdt	0.241**	-0.0181	0.148*	0.241**	-0.0171	0.118*
	(0.105)	(0.032)	(0.0880)	(0.105)	(0.0617)	(0.080)
Lgdp	0.0601***	0.049**	0.0668**	0.04***	0.055**	0.058***
	(0.0194)	(0.024)	(0.026)	(0.010)	(0.024)	(0.019)
Lgdp2	-0.020**	-0.023	-0.134**	-0.01**	-0.04*	-0.10**
	(0.0094)	(0.045)	(0.051)	(0.0044)	(0.027)	(0.049)
Lubn	0.0139	-1.28**	-0.123	0.0139	-1.177**	-0.123
	(1.5565)	(0.403)	(0.0924)	(1.5565)	(0.523)	(0.0924)
Lppu	0.149	0.466	-0.0341	0.149	0.466	-0.0341
	(0.8264)	(0.297)	(0.144)	(0.8264)	(0.297)	(0.144)
Constant			0.0193			0.0193
Observations	460	460	460	460	460	460
No. of crossid	22	22	22	22	22	22
country effect	YES	YES	YES	YES	YES	YES
year effect	NO	NO	NO	YES	YES	YES
YE_WT				0.981	0.07	1.230
Hansen_test		15.6	11.33		8.268	10.33
Sargan_test		16.25	16.44		8.437	6.337
AR(2)_test	-1.248	-1.236	-1.27	-0.894	0.676	-1.231
AR(3)_test	0.279			1.499		
S-H (OIR) test	18.944			-2.313		
No. of Instruments		18	19		17	19

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Instruments used are the lag values of the explanatory variables, S-H (OIR) represents the Sargan–Hansen (OIR) test. YE_WT is the Wald test of the year effect.

Accordingly, the estimated outcomes of the GMM (Table 4) provide several pieces of empirical evidence that, if used as a basis for policy measures, are capable of reducing carbon emissions and, by extension, enhancing environmental sustainability in the SSA if painstakingly implemented. What is crucial among such outcomes and similar to the estimates of the MM-QR is the influence of economic growth and the square of GDP, which confirms the hypothesis of the inverted U-form popularly known as the EKC. Judging from the three GMM-related estimation procedures – the linear and non-linear augmented sysGMM ($SGMM^1$) as proposed by Kripfganz, 2020, the sysGMM (SGMM), and the differenced GMM (DGMM) – the results indicate that economic growth (lgdp) largely increases CO_2 emissions and hence degrades environmental sustainability in the region. However, economic growth expansion ($lgdp^2$) largely reduces CO_2 emissions and hence improves the SSA region's environmental sustainability. The result obtained when the growth of GDP was used as a measure of economic growth further confirms the EKC supposition. This outcome, with the findings generated from MM-QR, supports the popular EKC hypothesis in line with the findings of Shahbaz et al. (2014), Rafindadi (2016), Mesagan and Olunkwa (2022), Khan et al. (2020), Marques et al. (2018), Farhani et al. (2014), and Osuntuyi and Lean (2022). Similarly, energy consumption significantly degrades environmental quality, as the increase in energy used elevates CO_2 emissions in the region. In specific terms, a one per cent increase in energy consumption increases CO_2 emissions by 0.141%, 0.245%, and 0.318% for the SGMM1, SGMM, and DGMM models, respectively. Obviously, DGMM exacerbates the environmental degradation the most following the increase in energy consumption. This result supports the observations of Rafindadi and Usman (2019) for South Africa, Mohiuddin et al. (2016) for Pakistan, Asumadu-Sarkodie and Owusu (2016) for Ghana, Shahbaz et al. (2014) for Tunisia, and Rafindadi (2016). Regarding financial development (lfdt), judging by the modified version of sysGMM (SGMM1), environmental quality is worsened, as CO_2 emissions increase following the increase in financial development in the region. This outcome substantiates the research outcomes of Musah et al. (2022) for West African countries, Boutafeh and Saadaoui (2020) for 18 selected African countries, Ye et al. (2020) for Malaysia, Nwani and Omoke (2020) for Brazil, and Ahmed et al. (2021) but contradicts the finding of Mesagan and Olunkwa (2022) for 18 African countries. The robustness checks carried out validate these outcomes reliably for policy implementation given the post-estimation tests; the tests show that the model is robust to AR (1) and AR (2) for the absence of first and higher-order autocorrelation and to the Sargan and Hansen tests as well as the Sargan–Hansen test *(OIR)* for instrument over-identification. The outcome from the Wald test of the year effect (YE_WT) indicates no joint effects of year in the panel models and this further validates the estimated outcomes.

5 CONCLUSIONS AND POLICY IMPLICATIONS OF THE FINDINGS

This study offers fresh insights into the heterogeneous determinants of environmental sustainability in the SSA region: the roles of energy consumption, economic growth, and financial development. Amidst other motivations, the dearth of updated empirical narratives from the above perspective as well as the twin econometric issues of heterogeneity and endogeneity inherent in the extant literature on the connection between environmental quality and growth compel the current evaluation. Based on this premise, our study used the novel MM-QR panel estimation procedure, which takes into account these dual econometric issues to estimate the magnitude-based influence of the listed explanatory variables on environmental sustainability. The relevant series from 22 SSA countries were analysed. Additionally, the sysGMM and its modified version, which captures non-linearity, were adopted for empirical estimates of the relevant series.

Our study demonstrates interesting outcomes, notably: Financial development significantly worsens the region's environmental quality; as the region's financial sector deepens, CO_2 emissions increase and thereby weakens environmental sustainability in the SSA region. The implication of this outcome is that while financial development as a driver of growth is worthwhile, its pursuit should not be to the detriment of environmental quality, so as to ensure environmental sustainability. As a result, authorities in the region must address both financial modernisation and programmes aimed at encouraging investment in environmentally friendly energy sources to improve energy conservation in the region, particularly in industrialised towns. Given the aforementioned, it is critical that regional policymakers include financial development initiatives in national environmentally friendly policy frameworks. Additionally, given that financial development via domestic financing to the private sector has a positive impact on carbon emissions, authorities in the region should give priority to such credit facilities. That is to say, only private companies who have integrated environmental protection techniques into their business operations and are ecologically conscientious should be eligible for such loan arrangements. This is to make sure that financial facilities of this kind do not encourage activities that negatively impact environmental quality.

In terms of our results, energy consumption has varying effects. Whereas at the upper quantiles, it increases CO_2 emissions substantially, the influence at the middle and low quantiles is inconsequential. This highlights the fact that the high level of energy use in the region significantly increases CO_2 emissions, which in turn reduces the region's environmental sustainability. The implication is that high-energy-consuming nations generate high CO_2 emissions and hence diminish environmental sustainability. Our empirical results also demonstrate that economic growth (lgdp) and its squared value ($lgdp^2$) confirm the inverted U-form hypothesis that at an initial developmental stage, economic growth increases carbon emissions (and degrades environmental quality) but at a later stage, after some progressive level of economic development, further economic growth results in a reduction in environmental degradation.

The potential for ecologically friendly resources, such as solar, wind, and perhaps geothermal energy, present the region with a significant natural edge. Instead of concentrating on generating energy from fossil resources, which has been shown to increase carbon emissions and eventually jeopardise environmental sustainability, Africa's large renewable potential in the form of solar and wind energy can be an environmental asset. Additionally, the region's nations must prepare green infrastructure development plans for vital economic sectors with high energy consumption, such as the industrial and transport sectors. If implemented in both urban and rural settings, such plans would benefit the region in two ways. Investment choices in environmentally friendly projects would first benefit the environment by guaranteeing a less polluting and higher-quality environment through the reduction of greenhouse gas emissions. Second, they would help the region counteract the increasing strain that rural-urban migration is placing on urban infrastructure, improving the general standard of living in urban settlements, and assisting in the achievement of SDG 11, which emphasises the need for sustainable cities and communities.

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