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Technological progress in achieving environmental sustainability in Central and Southern Africa: The role of fossil fuels and institutional quality

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ABSTRACT

In the face of growing efforts to achieve sustainable development Goal 7, 9, 13, and 16 in Africa, this study examines the environmental impacts of technological progress, fossil fuels, and institutional quality in achieving environmental sustainability in Central and Southern countries. The empirical analysis draws from a panel dataset spanning from 1996 to 2021, and utilizes the innovative method of Moments quantile regression technique, adjusted with the bootstrap variance algorithm and Half-Panel Jackknife (HPJ) Wald-type test with a bias-corrected pooled estimator. The findings reveal that fossil fuel consumption has a significant negative impact on sustainability. Surprisingly, institutional quality does not affect environmental outcomes. Central Africa faces challenges in adopting a sustainable technological path, while South African nations show a U-shaped relationship between technological progress and CO₂ emissions. In both Central and South Africa, high GDP per capita and fossil fuel consumption have a detrimental effect on environmental sustainability. In South Africa, there is bidirectional causality between CO₂ emissions and GDPsq, FOSSIL, while a unidirectional causality exists from fossil fuels to TECH. Overall, the study suggests a promising link between technological advancements and environmental sustainability in the South African region.

KEYWORDS

Africa; environmental sustainability; fossil fuels; institutional quality; Technological

1. Introduction

As we approach 2030, all sustainable development goals seem unattainable for most African countries due to several underlying factors. From the inception of the Kyoto protocol, all hands seemed to be on deck, especially in high-emitting countries toward reducing the level of carbon emissions worldwide. The growth disparity among countries worldwide seems to further worsen their ability to acquire environmental technologies and other carbon-reduction technologies to effectively curb environmental decimation and the adverse effect of climate change. This study recognizes the African situation alongside the growth disparities across Western Africa, Northern Africa, Central Africa, Eastern Africa, and Southern Africa.

There is a huge disconnect between empirical findings and reality about the technology-environmental sustainability nexus in the African case. Results from Danish Ulucak (2021), Erdogan (2021), and Udeagha and Ngepah (2023) portray substantial progress of technology in improving environmental protection in developing countries. Technological innovation is expected to engender cleaner environment through the auspices of green industrial structure, environmental

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technologies, and R&D. On the other hand, examining the level of technological progress from the past three or four decades shows no significant advancement across Central and Southern Africa (see Das and Drine 2020). For the umpteenth time, development in Africa is dependent on quality human capital, access to technology and capacity to absorb new technologies. Several doubts have been raised on the current state of technology to guarantee sustainable development across economic, social, and environmental pillars middle-income and low-income countries (see Omri 2020; Santana et al. 2015; Zhou et al. 2023).

There are some contextual issues that further impede the level of technological progress in Africa. The issues are not limited to finance, research, and development stagnation, poor institutions, and low quality of human capital (see Liu, Okere, and Muoneke 2023). The studies done by previous authors in the case of BRICS tend to misrepresent findings for some African economies. Indeed, Das and Drine (2020) boldly highlighted the distance of Africa from the technology frontier and reignited the call for efforts to close the gap. A critical example to highlight this gap is seen in the distance between the world average (2.71% as at 2021) on research and development as a percentage of GDP and most African economies accounting for 0.60% or less. Aside from the distance in Africa from the world average, the technology gap between environmental laggards in Africa and top emerging economies downplays their carbon-reduction potential.

This study derives its novelty from acknowledging the relevance of technological progress which captures incremental improvements in the technology of various Central and Southern African countries. The concept of technological progress is reinforced to capture the gradual progress made by Central and Southern African countries in moving from one technology state to a more improved technology state, especially industrial, energy-saving, and environmental technologies. Previous studies in advanced economies and the BRICS relied on technological innovation which carries its theoretically expected positive effect on environmental sustainability. In our study, we take a step further to focus on the incremental improvements to the existing state of technology and the factors hindering the investments in technological advancement and a speedy transition to carbon neutrality.

The scope of the study focuses solely on two critical factors identified that stagnates technological progress: (a) fossil fuel reliance and b) poor state of institutions in Africa. Continuous burning of fossil fuels to meet various demands in Central and Southern African countries prompts a decline in air quality, adverse effects of climate change and oil spillage. These environmental imbalances consume the limited financial resources expected to be channeled to investments in technological advancement (see Gao et al. 2023). The bar chart below shows the percentage of fossil fuels and renewable energy used by Central and Southern African countries to generate electricity.

Examining from the bar chart presented above (see Figure 1), Central Africa is more reliant on fossil fuels for electricity generation compared to Southern Africa. However, the quality of state bureaucrats in Africa is below average alongside the effectiveness of governance structures are not yet at the threshold to engender environmental sustainability. Corruption, lack of transparency and accountability and ecological fund misappropriation constitute doubt to futuristic investment in environmental protection projects and carbon-capture and removal technologies within Central and Southern Africa. Countries such as Chad, Congo Democratic Republic, Congo Republic, Zimbabwe, Central African Republic, Cameroon, Gabon, Eswatini, Zambia, and Angola are below the 40 on the 100 scale (see Transparency International Corruption Perception Index, 2023).¹ The above evidence depicts the high-level corruption and abuse of power within Central and Southern Africa.

The objective of this study is to investigate the relationship between technological progress and environmental sustainability amidst fossil fuels and institutional quality in Central and Southern Africa. Hence, the research questions are a) Does technological progress engender environmental sustainability in Central and Southern Africa? b) does fossil fuels and institutional quality influence the technological progress and environmental sustainability nexus in Central and Southern Africa? Several studies have investigated the technological innovations,

¹https://images.transparencycdn.org/images/Report_CPI2022_English.pdf

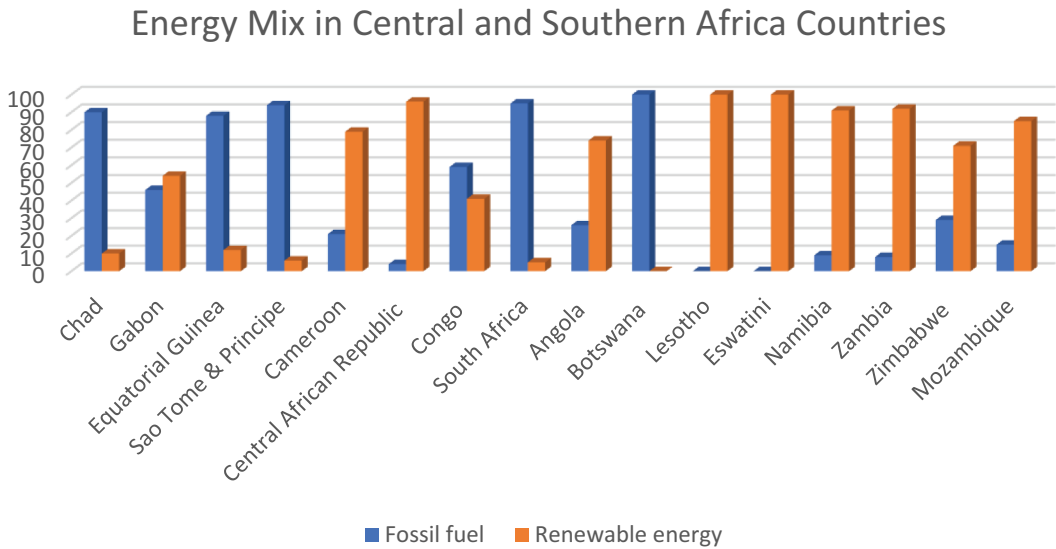


Figure 1. Energy mix in selected Central and Southern African Countries in 2021. Source: IRENA 2021

institutional quality and environmental sustainability nexus in advanced economies and emerging economies (Bhattacharya, Awaworyi, and Paramati 2017; Ganda 2019; Gyamfi et al. 2022; Nguyen, Pham, and Tram 2020; Shobande and Ogbeifun 2022; Solaymani and Montes 2023). Studies on the African scene lack insightful contribution to policy direction as most of the studies produced results defiant of current reality in the region of interest, especially the empirical efforts of Khan, Sampene, and Ali (2023). Aside from Central Africa, there is yet to be any intervention in the case of Southern Africa on the intersection between technological progress and environmental sustainability. This is the first attempt by any author to properly investigate the technological progress and environmental sustainability amidst the role of fossil fuels and institutional quality in Central and Southern Africa.

The contribution of this study to knowledge repository is outlined thus: (a) investigate the relationship between technological progress and environmental sustainability amidst the role of fossil fuels and institutional quality in Central and Southern Africa, (b) decipher causal directions between fossil fuels, technological progress, institutional quality, and environmental sustainability in Central and Southern Africa using Jackknife causality test technique propounded by Juodis, Karavias, and Sarafidis (2021), and (c) ascertain the threshold at which technological progress in sampled countries across Central and Southern Africa engenders environmental sustainability. This study is structured as follows: beyond the introduction, Section Two provides a thorough examination of previous research, Section Three outlines the practical steps and methods used, Section Four presents and discusses the findings, and finally, Section Five includes the conclusion and policy implications.

2. Literature review

The review of related studies is evaluated under three different strands: (a) technological innovation and environmental sustainability, (b) fossil fuels and environmental sustainability, and (c) institutional quality and environmental sustainability. Furthermore, a summary of key studies as seen in Appendix 1 is attached to further enrich the audience with vast empirical findings and methodological differences.

2.1. Technological innovation and environmental sustainability

The above-mentioned nexus represents the thrust of the empirical adventure as several studies have identified the distance between Africa and the technology frontier. The economic implications of investments in environmental-related innovations vary from high-income, middle-income, and low-income countries. Governments of most developing economies still dread the perceived implications of technology investment on economic prosperity (see Lasisi et al. 2022). Furthermore, the triad (affluence, population, and technology) provided by the influential STRIPAT model reinforces its association with environmental quality discourse in sub-Saharan Africa (see Aluko and Obalade 2020). Aside from its implications on economic prosperity, the issue of the U-shaped relationship between technological innovation and environmental sustainability raises some level of doubt about whether development of technology is desirable.

First, the existence of U-shaped relationship suggests that technology will reduce the level of carbon emissions in the short term due to the adoption of cleaner and more efficient technologies. On the other hand, the advancement of technology overtime, carbon emissions will take a notch higher than its previous level due to urbanization, increased energy consumption, reliance on fossil fuel powered industrial structure, improper e-waste disposal, ecosystem interruptions, pollution of water bodies and adoption of energy-intensive technologies. However, the capacity of individual countries to maintain the balance between positives and negatives associated with technology adoption remains the bone of contention. Submissions from Amari, Mouahkar, and Jarbouï (2022) continue to raise doubts on model specification, indicators used, econometric techniques and conceptualization of study. The results garnered from studies focused on emerging economies portray more of the inbuilt capacity of the BRICS to invest in cleaner environmental technologies and the presence of strong institutions to withstand the attributed negative effects through strong environmental regulation and practices (see Chien et al. 2021; Khan et al. 2020; Khattak et al. 2022). The situation is similar to most aspiring knowledge-based economies and current knowledge-based economies. The strength of their technical expertise in churning out sound scientific inventions and innovations toward ameliorating emissions-related issues associated with heavy industrialization alongside a strong institutional quality to mitigate negative effects associated with the transformation places them a step higher in the discussion of how to balance the positive and negative effects of technology adoption (see Liguó et al. 2023; Shobande and Ogbeifun 2022; Su et al. 2021).

The weakness of the countries in the Global South in mitigating the adverse effects of technology adoption raises continuous doubt on the U-shaped relationship between technological innovation and environmental sustainability. The positive results obtained by Amari, Mouahkar, and Jarbouï (2022) are only feasible alongside a functioning governance structure to mitigate the negative effects of technology adoption as seen in most emerging and advanced economies. Aluko and Obalade (2020) argued in line with the existing point that interactions between technological innovation and the present state of the financial system are dangerous to the environment in sub-Saharan Africa. This also connects with poor institutions incapable of dictating the direction of finance to green-compliant equipment, production activities, and technologies. As explained earlier, advancement of technology overtime might cause carbon emissions to increase beyond its previous level due to some underlying factors. Environmental technologies' advancement in Northern Africa has no positive effect on environmental quality in the long-term due to economic growth, renewable energy, and urbanization (see Shouwu et al. 2024). Country-wise, the capacity to withstand the negative effects of technology adoption may be higher in South Africa due to its advanced economy and position in global economic and political blocs. The adoption of technology to fully transform the industrial structure in South Africa and the willingness to utilize ICT in various sectors may account for reduction in the sectoral level of carbon emissions from non-electricity sectors in South Africa (see Ahmad et al. 2020; Villanthenkodath et al. 2022).

Our empirical intervention is to straighten up literature and offer empirical insights into the technological progress and environmental sustainability nexus alongside the effects of fossil fuels

and institutional quality in Central and Southern Africa. Our study distances itself from the empirical effort of Khan, Sampene, and Ali (2023) who focused on technological innovations, regulatory quality, government effectiveness, and environmental degradation nexus in CEMAC countries only. The results are highly questionable considering the heavy reliance on fossil fuels for electricity production in Central Africa. Furthermore, a multitude of studies relied on popular measures of technological innovation leading to similar patterns of results across all studies. Amidst all prevailing results stating that technological innovation engendering environmental quality in the region without a realistic connection, the authors thought it wise to utilize a more distinctive measure of technological progress (medium- and high-tech manufacturing value-added) to gauge the level of technological advancement overtime and its ability to overturn environmental imbalances in Central and Southern Africa.

2.2. Fossil fuels and environmental sustainability

The introduction of fossil fuels into the technological innovation and environmental sustainability nexus in Central and Southern Africa is influenced theoretically by the carbon curse theory (Friedrichs and Inderwildi, 2013) and the reliance on fossil fuels to meet local energy demand in some Central and Southern African countries. The perceived causality between fossil fuels and technological progress raised another important route for discussion. Continuous reliance on fossil fuels may divert clean investment financing to fossil-fuels technologies which frustrates the proposed energy transition plans in developing economies, especially in Africa (Asongu et al. 2022; Onifade 2023). The common factor driving most of these countries is the reliance on the exploration of fossil fuels to drive economic prosperity as seen in most South American countries and Asian countries (Muoneke, Okere, and Nwaeze 2022; Okere et al. 2021, 2022). Furthermore, the rush of some countries to achieve a wide variety of energy sources to meet energy demand creates a level of incompleteness and achieves low capacity to generate electricity in most of the sources. The efforts of some countries trying to achieve 100% capacity in renewable energy and nuclear energy lack the presence of adequate finance necessitating a partial or more significant reliance on fossil fuels in the short-term which contributes to environmental degradation (see Usman and Radulescu 2022).

2.3. Institutional quality and environmental sustainability

The level of technological progress and its impact on environmental sustainability is dependent on strong institutional arrangements to properly balance the positives and negatives in favor of the environment and economic prosperity. On one hand, developed nations have overcome the issues of economic instability to a greater extent compared to developing countries, especially in the Global South. Despite the negatives of technology on ecological stability, strong institutions in advanced economies put in necessary regulations and policies to mitigate the negative effects such as environmental laws on e-waste disposal, non-encroachment of protected land and other potent environmental regulations (see Solaymani and Montes 2023). On the other hand, the situation in developing countries is an eyesore characterized by weak regulatory frameworks, wide-scale corruption, use of government's veto to preempt bureaucratic delays, lack of transparency and accountability, and profiteering from fossil fuel projects.

Evidence from combined studies in the case of developed and developing economies portrays reducing effects on carbon emissions, which is misleading for policymakers (see Bhattacharya, Awaworyi, and Paramati 2017; Halder and Sethi 2021). There is lack of consensus in the upper echelon of developing countries (E-7 economies). Authors such as Gyamfi et al. (2022) and Saba et al. (2023) argues that the level of institutional quality and information and communication technology is not yet at the threshold to engender environmental quality in E-7 economies. The level of institutional quality in Mexico, Indonesia, and Turkey is questionable due to the findings of Hussain and Dogan (2021) positing that the level of institutional quality and environmental-related technologies reduced ecological footprint in BRICS economies. The

level of commitment to ensuring sustainable practices and building resilience to climate change in MINT economies is lower than the solid commitment by BRICS economies in ensuring cleaner and healthier environments through the adoption of green technologies and renewable energy sources.

Studies on the African scene produce mixed results which calls for the need to examine the subject under investigation region-by-region. North Africa has a huge grasp on technological advancement with some outlier countries such as South Africa and Mauritius as seen in the latest global innovation report for 2023. Therefore, relying on a unified continental study robs the readership of the true impact of institutional quality on environmental sustainability. Another important observation emanates from the neglect of technological innovation in the analysis of Wang et al. (2021) and Karim et al. (2022) which may be responsible for their results' alignment with established theory. Further reasons to object claims on institutional quality promoting environmental sustainability throughout Africa include the lack of freedom of press in some countries in the sub-region, lack of freedom of information, government crackdown on activists, suppression of the political opposition, internet censoring, and state-operated media. The importance of press freedom in ensuring freedom of expression and information on ecological projects, oil spillage, deforestation, mining, and reliance on fossil fuels is underrated in the African case (see Riti, Shu, and Kamah 2021).

This study narrowed its focus to Central and Southern Africa with few empirical entries on institutional quality and environmental sustainability nexus. Available empirical evidence in the region under review deviates from the findings of Wang et al. (2021) and Karim et al. (2022) for the entire Africa. Khan, Sampene, and Ali (2023) and Sah (2021) added that government effectiveness and regulatory quality present in Central African Economic and Monetary Authority (CEMAC) countries contributed to higher levels of environmental decimation. Regional-based studies in Central Africa refute the claims of continent-wide studies in the case of Africa. Azam et al. (2021) raised an important interjection in the face of the discourse stating that institutional quality is more poised to contribute to sustainable development in lower middle-income countries. All these strengthen the quest to test at the regional level and decipher region-specific effects that may question the status quo. There is a dearth of studies in regional Africa to substantiate a plethora of claims made by a multitude of authors focused on continent-wide studies (Africa and sub-Saharan Africa).

3. Methods and data

3.1. Development of a theoretical framework and the construction of a model

The theoretical framework and the construction of the model are derived in the STIRPAT (Stochastic Impacts via Regression on Population, Affluence, and Technology) framework, initially proposed by Dietz and Rosa (1994). The STIRPAT equation, utilized for examining the factors that influence environmental effect, can be expressed as follows:

$$I_t = \beta_0 * P_{it}^{\beta_1} * A_{it}^{\beta_2} * T_{it}^{\beta_3} * \varepsilon_{it} \quad (1)$$

Equation (1) expresses the relationship between environmental impact (I) and population (P), affluence (A), and technology (T), where these factors can be measured using different metrics. The impact component (I) in this inquiry is dependent on the CO₂ emission. The population of a country is determined by the number of residents it has. Affluence (A) is measured by the GDP per capita. The impact of technology is evaluated by examining the technological progression, with a focus on increasing the capacity for medium- and high-tech output. This study introduces a significant enhancement to the conventional STIRPAT equation by including the level of economic dependence of selected African nations on fossil fuel consumption, institutional quality, and technological progression (see Nwani et al. 2023). Based on these definitions, Equation (1) is subjected to algebraic manipulation in order to build an empirical model that guides this analysis.

$$\ln CO2_{it} = \beta_0 + \beta_1 \ln P_{it} + \beta_2 \ln GDP_{it} + \beta_3 \ln FOSSIL_{it} + \beta_4 PCA - IQ_{it} + \beta_5 TECH_{it} + \varepsilon_{it} \quad (2)$$

The variables in Equation (2) are logarithmically transformed using the natural logarithm notation, denoted as “ln.” The subscripts i and t indicate the specific country i during the particular year t , whereas ε denotes the random error term. The I_t is denoted as CO2, whereas FOSSIL, PCA-IQ² and TECH³ are used as indices for dependence on natural resources, institutional quality and technology progression, respectively. The model has the constant term β_0 and elasticity coefficients ($\beta_1 \dots \beta_5$) for the explanatory variables. The model is extended to account for the EKC hypothesis and the intensity of fossil fuel dependence:

$$\ln CO2_{it} = \beta_0 + \beta_1 \ln P_{it} + \beta_2 \ln GDP_{it} + \beta_{2sq} \ln GDPsq_{it} + \beta_3 \ln FOSSIL_{it} + \beta_4 PCA - IQ_{it} + \beta_5 TECH_{it} + \varepsilon_{it} \quad (3)$$

A valid inverse U-shaped association between income and CO2 emissions is confirmed when the income variable $\beta_2 > 0$ has a positive coefficient, and the squared income variable $\beta_{2sq} < 0$ has a negative coefficient. Any deviations from this pattern in the combinations of coefficients indicate a deviation from the hypothesis of the Environmental Kuznets Curve (EKC). Theoretically, we expect $\beta_3 > 0$ and $\beta_4 < 0$. To account for the technological progress that triggers the carbon mitigation, the functional relationship in Eq. (3) is augmented with the quadratic term of TECH variable as follows:

$$\begin{aligned} \ln CO2_{it} = & \beta_0 + \beta_1 \ln P_{it} + \beta_2 \ln GDP_{it} + \beta_{2sq} \ln GDPsq_{it} + \beta_3 \ln FOSSIL_{it} + \beta_4 PCA - IQ_{it} + \beta_5 \ln TECH_{it} \\ & + \beta_{5sq} \ln TECHsq_{it} + \varepsilon_{it} \end{aligned} \quad (4)$$

When TECHsq represents the quadratic term signifying an elevated level of TECH, a valid U-shaped relationship between CO2 and TECH is confirmed if $\beta_5 < 0$ and $\beta_{5sq} > 0$. This relationship suggests that the effectiveness of carbon mitigation intensifies as the economic reliance on technological progression increases. The turning point of this relationship is determined by setting the derivative of Equation (4) equal to zero, resulting in: $\ln TECH_{it} = -\beta_5 / 2\beta_{5sq}$

3.2. Data and sources

The study employs data collected from 1996 to 2021, with a specific emphasis on 16 African nations (see Appendix D). The variables are sourced from the World Development Indicators (WDI). The choice to restrict the sample period is mainly motivated by the significant prevalence of missing data in the technical progress variables for the majority of African nations prior to 1996. Therefore, this limitation is crucial in order to improve the representation of the section by incorporating a greater number of nations in the sample. Moreover, in order to achieve the empirical study's goal of comparing the effects on technological progression, reliance on fossil fuels, and institutional quality on environmental sustainability in Central and Southern Africa, it is essential to divide the complete sample according to regional differences. Hence, the sample is partitioned into two distinct sub-samples, namely Central Africa and Southern Africa, in order to clarify the differences seen between these two sub-regions.

3.3. Descriptive statistics

The variables are summarized in Appendix D using basic descriptive statistics. CO2 amounts to 6.480 tonnes, and the skewness is positive and 0.518 indicates a rightward skew, indicating that a few countries have considerably higher emissions than the average (see also Figures 2 and 3: Plot A). The

²A detailed explanation of the variables mentioned in Note 1 and Appendix D relate.

³Details explanation of the variables in highlighted in the Appendix D and Note 2 respectively.

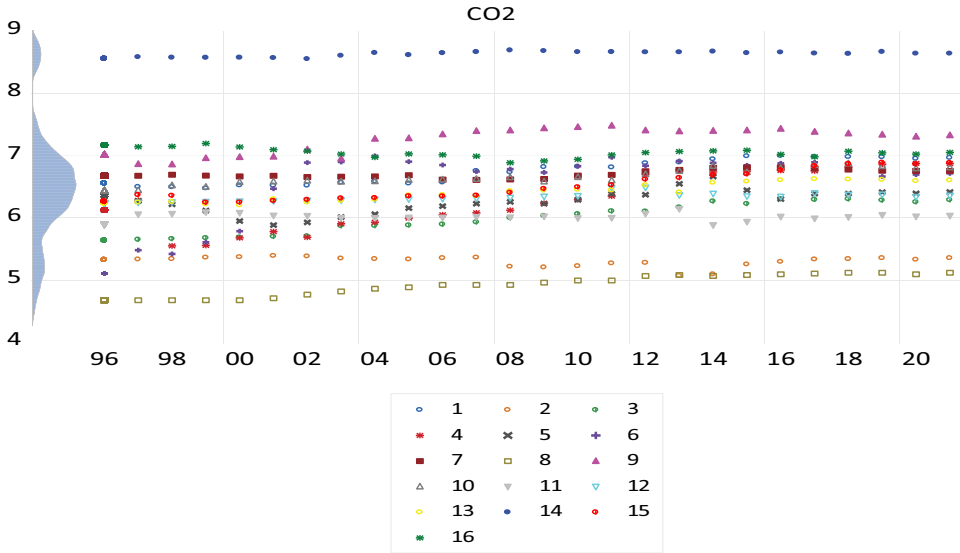


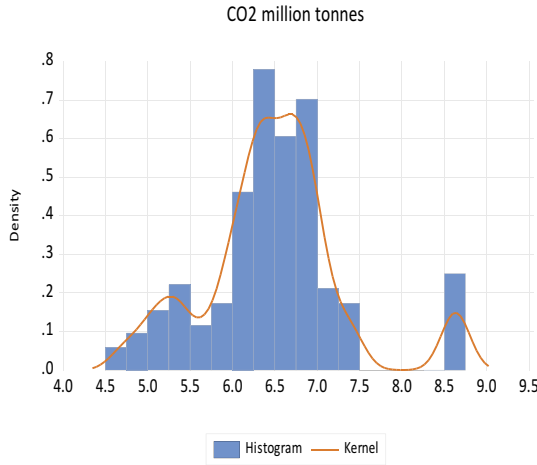
Figure 2. Distributional plots CO2.

mean and median values for the overall population are, respectively, around 6.694 million and 6.644 million, respectively. The distribution of GDP per capita average and middle value of roughly 3.584 and 3.554, respectively. The data on fossil fuel consumption have a negative skewness of 0.652, indicating a more pronounced right tail. This indicates a less effective utilization of energy resources and a significant reliance on fossil fuels, such as coal, oil, and natural gas, in the region (see Figure 3: Plot B). The PCA-IQ data show a positive skewness of 0.395, indicating a rightward skew or a longer right tail. The presence of a positive skewness value of 0.131 in the percentage of technological progress (medium- and high-tech manufacturing value added) suggests that the distribution is skewed to the right, with a larger tail on the right side. Certain countries exhibit proportions that above the average, indicating a focus on technologically advanced industries. Finally, the correlation from the lower part Appendix D, there is no evidence of multicollinearity among the variables. The wide range description statistics cannot give a big picture of the interplay among the variables; thus, empirical investigation is necessary for policy decisions.

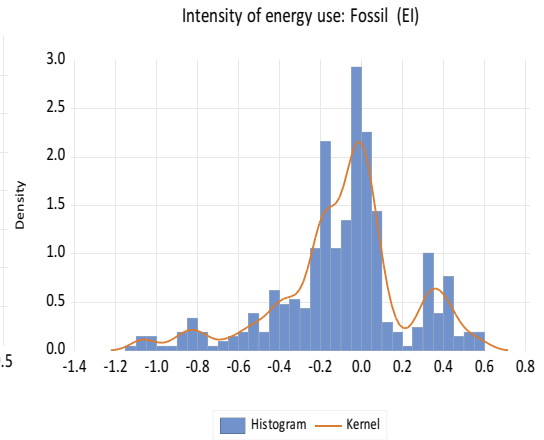
3.4. Estimation of technique

To obtain initial estimations for different specifications of Equations (2 and 3), we employ the Fixed Effect Driscoll – Kraay (DK) regression methods. This approach utilizes standard errors that are resilient to both cross-sectional and temporal dependencies in a general form (Driscoll and Kraay 1998). However, a notable limitation of the FE-DK regression technique is its focus solely on modeling the conditional mean of the dependent variable. To address this limitation and capture additional aspects of the conditional distribution of CO2, our study adopts the method of moments quantile regression (MM-QR) proposed by Machado and Silva (2019) to handle fixed effects in panel quantile models. By utilizing the MM-QR estimator, we investigate the influence of technological progress, fossil fuels, and institutional quality on the lower, median, and upper distributions of CO2 in Central and Southern Africa. Unlike some other panel quantile regression methods (e.g., Canay 2011; Galvao 2011), the MM-QR estimator yields robust and valid estimates without necessitating strong distributional assumptions. Notably, the MM-QR algorithm stands out by generating regression quantiles based on the conditional location-scale shift model. This unique feature allows individual effects to impact the entire distribution, enhancing the robustness

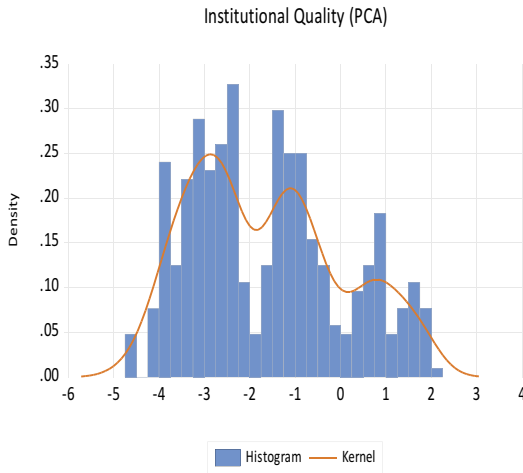
PLOT A



PLOT B



PLOT C



PLOT D

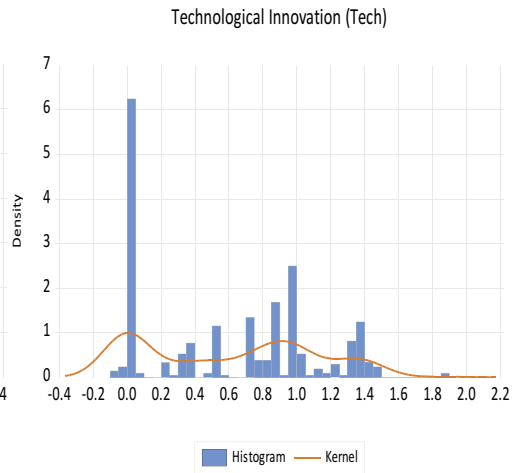


Figure 3. Histogram and Gaussian Kernel density plots for key variables.

of the MM-QR approach. Consequently, it has become the preferred quantile regression technique in recent literature, distinguishing itself from procedures employed in studies such as Canay (2011) and Galvao (2011).

The estimation methodology for the conditional quantile $Q_y(\tau|X_{it})$ of the location-scale variant model is derived by modifying Equations 2 & 3 based on the methodologies proposed by Machado and Silva (2019). The broad specification is employed to adjust the equations:

$$Q_y(\tau|X_{it}) = (\beta_i + \delta_i q_i) + X'_{it}\beta + Z'_{it}\gamma q(\tau) \quad (5)$$

where $Q_y(\tau|X_{it})$ depict the quantile distribution of the dependent variable $\ln Y_{it}$, conditional on the location and scale of explanatory variable (X'_{it}) . X'_{it} it is a vector of explanatory variables. $\alpha_i(\tau) = \alpha_i + \delta_i q(\tau)$ represents the distributional effect at τ or the scalar coefficient of the quantile- τ fixed effect for individual i . $q(\tau)$ is the τ -th quantile estimated through optimization function:

$$\min_q \sum_i \sum_t \rho_\tau(\hat{R}_{it} - (\hat{\delta}_i + Z'_{it}\hat{\gamma})q) \quad (6)$$

Accordingly, this threshold $\rho_\tau(A) = (\tau - 1)AI\{A \leq 0\} + \tau AI\{A > 0\}$ offers a check-function. Drawing from the Eq. (5), we present the final modified baseline model stated in equ.2 & 3 for panel quantile calculation as thus

$$Q_{Y_{it}}(\tau|\beta_i, \varepsilon_{it}, X_{it}) = \beta_0 + \beta X_{it} + \gamma Z_{it} + \delta_{it} + \varepsilon_{it} \quad (7)$$

The quantile model presented in Equations (7) considers the distributional effects of explanatory variables on the explained variable, and also accounts for the impact of technological progress, fossil fuels and institutional quality in Central and Southern African region.

4. Regression estimates and discussion of findings

4.1. Results of preliminary tests

Table 1 presents the results of the Pesaran (2021) test, which evaluates cross-sectional dependence. The test statistics indicate that the null hypothesis of cross-sectional independence is rejected for the indicated variables: CO2, P, GDP, GDPSQ, PCA-IQ, TECH, and TECHSQ. This indicates the presence of cross-sectional dependence within the data series. Therefore, the null hypothesis is rejected for all series. The results of the slope homogeneity test, performed using the Pesaran and Yamagata (2008) test, are displayed in Table 2, Panel A. The test statistics demonstrate that the null hypothesis of homogeneity of slope coefficients across all equations is rejected, indicating the existence of different slope coefficients in the model specifications. To account for the cross-sectional dependence detected in the data series, an analysis is performed to assess the integrating qualities of the variables in the presence of this dependence. This is accomplished by employing a second-generation panel unit root testing technique, namely the CIPS test developed by Pesaran (2007), which relies on more robust truncated statistics.⁴ The results presented in Table 2, Panel B, indicate that when cross-sectional dependency is taken into account, the variables do not exhibit stationarity in their levels. Therefore, they display stationarity when considering the differences between consecutive values. Put simply, the variables adhere to a first-order integrated (I(1)) process. Once we have determined the integrating qualities of the variables, our next objective is to verify the existence of cointegration among them. The

Table 1. Pesaran (2004, 2015) cross-section dependence and second-generation panel unit root tests.

Variable	Panel A						Panel B: CIPS-TR			
	Full Sample		Central Africa		South Africa		At level form		At first difference form	
	CD-test	CD-test	CD-test	CD-test	CD-test	CD-test	CIPS	Truncated CIPS	CIPS	Truncated CIPS
CO2	21.031***	21.031***	11.603***	11.603***	7.272***	7.272***	-2.793**	-2.793**	-5.298***	-4.976***
P	54.693***	54.693***	26.853***	26.853***	26.143***	26.143***	-0.2578	-0.491	-2.354***	-2.354***
GDP	29.984***	29.984***	12.668***	12.668***	14.857***	14.857***	-2.219	-2.210	-3.811***	-3.811***
GDPSQ	29.957***	29.957***	12.625***	12.625***	14.876***	14.876***	-2.143	-2.143	-3.753***	-3.753***
FOSSIL	3.437***	3.437***	3.416**	-2.416**	6.463***	6.463***	-1.649	-1.649	-4.273***	-4.110***
PCA-IQ	3.986***	3.986***	2.283**	-2.283**	8.158***	8.158***	-1.700	-1.700	-3.882***	-3.882***
TECH	2.404***	3.404***	2.156**	-2.156**	1.830**	1.830*	-1.370	-1.370	-4.772***	-4.772***
TECHSQ		3.401***		-2.039**		1.897*	-1.255	-1.255	-4.743***	-4.743***

CIPS-TR-Pesaran (2007) CD-adjusted (Second-generation) panel unit root tests.

*** $p < 0.01$ indicates significance at 1% level.

⁴The regression out is generated using eviews 12.

Table 2. Slope homogeneity and Pedroni Cointegration tests.

Test	Test of Spec.	Algorithm	Full Sample		Central Africa		South Africa	
			MODEL 1: NO TECHSQ	MODEL 2: TECHSQ	MODEL 1: NO TECHSQ	MODEL 2: TECHSQ	MODEL 1: NO TECHSQ	MODEL 2: TECHSQ
Panel A	Slope homogeneity	Pesaran and Yamagata (2008) Delta tilde ($\tilde{\Delta}$)	13.194***	11.267***	9.922***	8.364***	8.814***	6.933***
			0.000	0.000	0.000	0.000	0.000	0.000
		Adjusted delta tilde ($\tilde{\Delta}$)	15.857***	13.933***	11.925***	10.343***	10.593***	8.574***
			0.000	0.000	0.000	0.000	0.000	0.000
			0.000	0.000	0.000	0.000	0.000	0.000
Panel B	Test	Stats.	Panel	Group	Panel	Group	Panel	Group
		v	−0.6033	.	−0.4092	.	−0.758	.
		Without TECHSQ	0.9889	2.389***	1.065	2.160***	0.4533	1.43
		t	−5.451***	−5.848***	−2.899***	−2.79***	−4.248***	−4.85***
		adf	−1.935***	−1.901***	−2.491***	−2.014***	−1.942***	−2.811***
		With TECHSQ	−1.308	.	−0.8732	.	−1.109	.
		rho	2.015***	3.455***	1.988***	3.029***	1.29	2.293***
		t	−5.826***	−6.459***	−2.194***	−2.228***	−3.991***	−4.379***
		adf	−0.9015	−0.4821	−1.859***	−1.989***	−1.347	−1.549*

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

results of the Pedroni Cointegration test, taking into account the number of variables in our model, are displayed in Table 2, Panel B. The results reveal that there is panel cointegration present for the two equations, as evidenced by the v, rho, t, and adf statistics. This holds true regardless of any adjustments made to the variable combinations. In order to enhance the reliability of the parameter estimates, we employ the FE-DK and MMQR estimator. This estimator is selected for its effectiveness in dealing with panels that have nonstationary variables, whether they are cointegrated or not, and multifactor error components that indicate cross-section dependence.

4.2. Results full sample

The estimations are obtained via the FE-DK and MM-QR panel quantile regression, which accounts for changes in the environmental implications of CO2 emission patterns among the chosen nations. The three quantile sections are as follows: the lower quantile (qtile_25th) consists of countries such as Botswana, Central African Republic, Chad, Congo, Equatorial Guinea, Eswatini, Gabon, Lesotho, Namibia, Sao Tome and Principe, Zambia, and Zimbabwe; the median quantile (qtile_50th) comprises countries like Angola, Democratic Republic of Congo, and Cameroon; and the upper quantile (qtile_75th) includes countries like South Africa.⁵

Starting with the FE-DK panel analysis in Table 3, the population coefficient is predictably positive and statistically significant at the 1% level. In addition, the MM-QR estimates (columns 5–7) offer further evidence suggesting a stronger environmental impact in certain economies across the quantile. The observed result is consistent with the theoretical predictions (see Rosa and Dietz 2012), indicating that the increase in population has a substantial impact on the emission of CO2 in these nations. This finding is in tandem Aluko and Obalade (2020) in case of sub-Saharan Africa. The findings also suggest that the coefficients of per capita GDP (A) and the quadratic-term GDPsq are positive but lack statistical significance in their relationship with CO2 emissions in the nations, according to the FE-DK estimates (columns 1 & 2). The parameter estimations indicate that the Environmental Kuznets Curve (EKC) theory does not apply to this particular set of economies. MM-QR estimations indicate that the

⁵See Figure 2

Table 3. Full sample.

Variables	1	2	3	4	5	6	7	8	9	10	11	12
	FE-DK	FE-DK	location	scale	qtile_25	qtile_50	qtile_75	location	scale	qtile_25	qtile_50	qtile_75
P	0.802*** (0.177)	0.774*** (0.181)	0.802*** (0.152)	0.00549 (0.085)	0.797*** (0.147)	0.802*** (0.153)	0.807*** (0.190)	0.774*** (0.155)	-0.008 (0.086)	0.781*** (0.150)	0.773*** (0.156)	0.766*** (0.193)
GDP	0.78 (0.573)	0.737 (0.550)	0.780** (0.394)	-0.053 (0.249)	0.825* (0.441)	0.779** (0.394)	0.733 (0.459)	0.737* (0.398)	-0.0931 (0.250)	0.817* (0.448)	0.732* (0.399)	0.652 (0.463)
GDPSQ	0.0153 (0.077)	0.0246 (0.074)	0.0153 (0.057)	0.00288 (0.036)	0.0129 (0.063)	0.0154 (0.057)	0.0179 (0.066)	0.0246 (0.058)	0.0095 (0.036)	0.0164 (0.065)	0.0251 (0.058)	0.0332 (0.067)
FOSSIL	0.585*** (0.041)	0.564*** (0.041)	0.585*** (0.074)	-0.0866* (0.046)	0.660*** (0.063)	0.584*** (0.075)	0.509*** (0.102)	0.564*** (0.076)	-0.0927** (0.046)	0.644*** (0.066)	0.560*** (0.078)	0.480*** (0.104)
PCA-IQ	0.0183* (0.010)	0.0182* (0.009)	0.0183* (0.009)	0.00168 (0.005)	0.0169 (0.011)	0.0183* (0.010)	0.0198* (0.011)	0.0182* (0.010)	0.000643 (0.005)	0.0177 (0.011)	0.0183* (0.010)	0.0188* (0.011)
TECH	-0.124*** (0.043)	-0.335*** (0.072)	-0.124*** (0.042)	-0.0412* (0.021)	-0.0885** (0.043)	-0.125*** (0.043)	-0.160*** (0.049)	-0.335*** (0.112)	-0.0903 (0.057)	-0.257** (0.116)	-0.340*** (0.113)	-0.417*** (0.130)
TECHsq		0.125*** (0.032)						0.125*** (0.046)	0.0189 (0.024)	0.109** (0.048)	0.126*** (0.046)	0.142*** (0.054)
Threshold		1.3400						1.3400	2.3889	1.1789	1.3492	1.4683
Threshold (% TECH)		3.8190						3.8190	10.9014	3.2508	3.8544	4.3419
Constant	-1.723 (1.640)	-1.455 (1.646)	-1.723 (1.206)	0.21 (0.740)	-1.904 (1.270)	-1.719 (1.208)	-1.538 (1.460)	-1.455 (1.234)	0.372 (0.744)	-1.775 (1.313)	-1.436 (1.238)	-1.116 (1.480)
Observations	416	416	416	416	416	416	416	416	416	416	416	416

Mva = (% manufacturing value added) Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

coefficients of GDP (A) and the quadratic-term GDPsq are statistically negligible in nations that fall within the upper quantile (MM-qtile_75) of the distribution. Nevertheless, the GDP estimates for the lower (MM-qtile_25) and median quantile (MM-qtile_50) of the distribution, as shown in [Figure 3](#), provide evidence of a constantly rising relationship between per capita income and CO₂ emissions, which contradicts the FE-DK estimates. This variation can be attributed to changes in the ways environmental indicators are measured. The EKC hypothesis is not applicable to CO₂ emissions in the chosen emerging regional economies. Therefore, using economic measures to tackle the increase in CO₂ emissions in these local economies would be ineffective and may not produce the desired outcomes.

The coefficient of elasticity for Fossil fuel is positive and statistically significant. This indicates that a percentage increase in energy intensity (specifically from fossil fuels) leads to a corresponding increase of 0.585% and 0.564% in CO₂ emissions, as shown in columns 1 and 2. In essence, a higher fossil fuel means that more energy is needed to produce the same economic output, which could result in increased use of resources and environmental stress. The escalated energy demand can lead to amplified emissions, contamination of air and water, and exhaustion of resources. This finding questions the efficacy of the UN SDG 7.3 objective in promoting efforts to enhance energy efficiency and reduce CO₂ emissions in the chosen economies. The estimates obtained from the MM-QR model parameters in columns 5–7 and 10–12 confirm the presence of a positive coefficient for Fossil Fuel. The effect is more noticeable and worsening at the lower quartile (MM-quartile_25). Based on the estimations, nations in the lower quantile see a more significant rise in CO₂ emissions for each unit increase in Fossil fuel compared to countries in the upper quantile. This findings followed the collective efforts of Asongu et al. (2020) who confirmed that fossil fuels consumption contributed to environmental degradation in Africa. Okere et al. (2022), Muoneke, Okere, and Nwaeze (2022) and Okere et al. (2021) attest to the fact that fossil fuels consumption in Peru, the Philippines, and Argentina. The impact of institutional quality within the region is another factor that contributes to environmental deterioration. The results obtained using FE-DK (Column 1 & 2) indicate that a rise in PCA-IQ by a certain percentage corresponds to a 0.0183% and 0.0182% increase in CO₂ emissions, respectively. The MM-QR model parameters in columns 5–7 and 10–12 provide additional evidence supporting the existence of a positive coefficient for PCA-IQ. Notably, these coefficients are found to have no statistical significance. Surprisingly, institutional considerations do not seem to reduce environmental deterioration in the chosen African countries. These findings challenge prior research, such as the study conducted by (Haldar and Sethi 2021; Solaymani and Montes 2023) which found significant beneficial impacts of institutional elements on environmental sustainability. The present findings are consistent with an increasing amount of empirical submission, which includes research conducted by Hussain and Dogan (2021) Hussain and Dogan (2021). This research result aligns with Saba et al. (2023) Gyamfi et al. (2022) study, which presents multiple argument. First, it indicates that the institutional changes in certain African countries may not be well constructed to strengthen regulatory systems against the impacts of human activities and resource depletion on the ecosystem. Second, it suggests that there are inherent vulnerabilities and shortcomings in the institutional structure that governs resource extraction operations in African nations. Third, it suggests that the institutions in the subregion may not meet the required criteria to effectively promote structural transformation that can transition from pollution-intensive technologies to cleaner and more environmentally sustainable production methods.

The analysis of technological advances offers a fascinating approach to comprehend the environmental impact of CO₂ emissions in the selected African area, similar to empirical evidence from Amari, Mouahkar, and Jarbouli (2022), Naeem et al. (2023), and Sakariyahu et al. (2023). The coefficient estimates for the variables TECH and TECHsq in columns 1 and 2 demonstrate statistical significance at the 1% level. The coefficient for TECH is negative, while the coefficient for TECHsq is positive. The results confirm the existence of the U-shaped relationship between technological progress and CO₂ emissions in the selected countries. The MM-QR technique yields comparable results when used to columns 10–12.

Based on SDG 17.6, an optimal comprehension of the adjustment pattern can be attained by analyzing the threshold, or turning point, of technological advancement. In the case of FE-DK, the minimum value required to support the EKC hypothesis is 3.819% (found in column 2). On the other hand, MMQR shows a rise from 3.250% at the 25th percentile to 4.341% at the 75th percentile. This pattern indicates that the threshold technological progress is not constant, as indicated by estimates from conditional mean estimation methodologies (FE-DK). However, the amount differs depending on the carbon emission level of the country. The variation in threshold estimates suggests that countries with higher CO₂ emissions are likely to achieve technological progress faster, as they require a greater level of technological advancement compared to countries with lower CO₂ emissions, which require higher technological advancement to reach their threshold. From the policy standpoint, at the initial stages of technological advancement, there is a potential for heightened environmental impact due to resource exploitation, the utilization of harmful technologies, and inadequate environmental regulations. However, there might be a transitional phase during which the environmental impact peaks. During this stage, increased consciousness regarding environmental concerns may result in the adoption of more environmentally friendly technologies, the enforcement of environmental policies, and additional technological progress. These advancements can stimulate the acceptance of sustainable technologies, the efficient execution of environmental legislation, and the encouragement of eco-friendly practices. As a result, there is a reduction in the negative effects on the environment, even while the economy continues to grow.

4.3. Sub-sample result

To resolve the issue of mixed findings as envisaged in the full sample, the sub-sample test examines regional variations in FOSSIL, PCA-IQ, and TECH. To streamline our argument, we concentrate on key variables. The estimates in Tables 4 and 5 reveal a positive and statistically significant relationship in FE-DK and in MM-QR for all the quantile sections of Fossil. The PCA-IQ coefficient is positive but insignificant in both Central and South Africa, aligning with previously reported evidence in the complete sample. The absence of a U-shaped relationship between CO₂ emissions and technological progress was not noted in Table 4 for Central Africa; thus, we cannot compute the threshold, which is similar to evidence in the case of Asongu, Roux, and Biekpe (2018); Shouwu et al. (2024). However, in Table 5, our results indicate the presence of a U-shaped relationship between CO₂ emissions and technological progress in South African countries. Specifically, TECH and TECHSQ demonstrate negative and positive effects on CO₂ emissions, respectively. This suggests that environmental deterioration often rises during the initial phases of economic progress, but gradually declines once a specific level of money or technological innovation is achieved. In line with this idea, during the early stages of economic development, the process of industrialization and increasing production frequently leads to a rise in pollution and the depletion of resources. Nevertheless, when a civilization progresses in terms of income and technological advancement, it acquires the ability to allocate resources toward cleaner technologies and environmental conservation efforts, resulting in a reduction in environmental deterioration.

The results presented in Table 5 also reveal a compelling aspect – the existence of a U-shaped relationship between CO₂ emissions and technological progress. This implies that the trajectory toward environmental sustainability through technological advancement is viable only once a country attains a specific level of technological progress. The turning point, estimated to be within the range of 2.6216–2.6557% of TECH, serves as the threshold for technological progress. Beyond this threshold, further advancements are anticipated to contribute positively to carbon neutrality in the region. This additional empirical insight elucidates why previous studies (see Lasisi et al. 2022, Chien et al. 2021, Asongu, Roux, and Biekpe 2018, Shouwu et al. 2024, Villanthenkodath et al. 2022) employing panel selection of countries with diverse technological capacities and resources, have yielded inconclusive policy recommendations.



Table 4. Central Africa.

Variables	1	2	3	4	5	6	7	8	9	10	11	12
	FE-DK	FE-DK	location	scale	qtile_25	qtile_50	qtile_75	location	scale	qtile_25	qtile_50	qtile_75
P	0.671*** (0.220)	0.647*** (0.210)	0.671*** (0.205)	-0.108 (0.121)	0.768*** (0.190)	0.668*** (0.206)	0.576** (0.265)	0.647*** (0.204)	-0.124 (0.116)	0.759*** (0.192)	0.637*** (0.207)	0.535** (0.261)
GDP	0.83 (0.595)	0.782 (0.598)	0.83 (0.512)	-0.168 (0.325)	0.981* (0.546)	0.825 (0.513)	0.683 (0.622)	0.782 (0.511)	-0.198 (0.323)	0.960* (0.555)	0.767 (0.514)	0.603 (0.617)
GDPsq	0.0315 (0.081)	0.0394 (0.081)	0.0315 (0.078)	0.0252 (0.048)	0.00895 (0.080)	0.0323 (0.078)	0.0537 (0.096)	0.0394 (0.078)	0.0296 (0.047)	0.0128 (0.082)	0.0417 (0.078)	0.0661 (0.095)
FOSSIL	0.558*** (0.075)	0.548*** (0.073)	0.558*** (0.122)	-0.0529 (0.076)	0.605*** (0.095)	0.556*** (0.123)	0.511*** (0.172)	0.548*** (0.121)	-0.0524 (0.073)	0.595*** (0.096)	0.544*** (0.124)	0.500*** (0.169)
PCA-IQ	0.0138 (0.013)	0.0162 (0.013)	0.0138 (0.017)	-0.00791 (0.010)	0.0208 (0.019)	0.0135 (0.017)	0.0068 (0.019)	0.0162 (0.017)	-0.00781 (0.009)	0.0232 (0.019)	0.0156 (0.017)	0.0091 (0.018)
TECH	-0.269** (0.119)	1.425** (0.569)	-0.269** (0.125)	-0.109 (0.067)	-0.171 (0.138)	-0.272** (0.127)	-0.365** (0.140)	1.425** (0.660)	1.320*** (0.276)	0.241 (0.743)	1.528** (0.677)	2.618*** (0.709)
TECHsq		-1.185*** (0.405)						-1.185*** (0.447)	-0.975*** (0.195)	-0.309 (0.518)	-1.260 (0.459)	-2.066 (0.473)
Threshold												
Threshold (% TECH)												
Constant	-1.342 (1.801)	-1.381 (1.697)	-1.342 (1.562)	1.087 (0.960)	-2.313 (1.626)	-1.309 (1.566)	-0.387 (1.906)	-1.381 (1.510)	1.005 (0.925)	-2.283 (1.585)	-1.303 (1.522)	-0.473 (1.844)
Observations	208	208	208	208	208	208	208	208	208	208	208	208

Standard errors in parentheses.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 5. Sub-sample: South Africa.

Variables	1	2	3	4	5	6	7	8	9	10	11	12
	FE-DK	FE-DK	location	scale	qtile_25	qtile_50	qtile_75	location	scale	qtile_25	qtile_50	qtile_75
P	0.702*** (0.157)	0.620*** (0.153)	0.702*** (0.195)	0.225*** (0.076)	0.504** (0.198)	0.691*** (0.196)	0.914*** (0.224)	0.620*** (0.195)	0.236*** (0.075)	0.409** (0.200)	0.614*** (0.198)	0.827*** (0.222)
GDP	1.915** (0.735)	1.789** (0.675)	1.915*** (0.604)	0.085 (0.315)	1.840*** (0.537)	1.910*** (0.598)	1.995** (0.787)	1.789*** (0.626)	0.273 (0.321)	1.546*** (0.563)	1.782*** (0.624)	2.029*** (0.800)
GDPsq	-0.183* (0.098)	-0.160* (0.092)	-0.183** (0.084)	-0.0188 (0.043)	-0.167** (0.074)	-0.182** (0.083)	-0.201* (0.109)	-0.160* (0.087)	-0.0439 (0.043)	-0.121 (0.078)	-0.159* (0.087)	-0.198* (0.111)
Fossil	0.177*** (0.045)	0.141*** (0.044)	0.177*** (0.054)	-0.00587 (0.026)	0.183*** (0.053)	0.178*** (0.054)	0.172*** (0.066)	0.141*** (0.049)	-0.00197 (0.024)	0.143*** (0.050)	0.141*** (0.049)	0.139** (0.056)
PCA-IQ	0.00718 (0.010)	0.00734 (0.009)	0.00718 (0.007)	0.00596 (0.004)	0.0195 (0.007)	0.00689 (0.007)	0.0128 (0.008)	0.00734 (0.007)	0.00487 (0.004)	0.003 (0.007)	0.00721 (0.007)	0.0116 (0.008)
TECH	-0.0165 (0.038)	-0.230** (0.085)	-0.0165 (0.023)	-0.0182 (0.015)	-0.0053** (0.025)	-0.0156** (0.023)	-0.0336** (0.028)	-0.230*** (0.068)	-0.0414 (0.038)	-0.193*** (0.071)	-0.229*** (0.068)	-0.266*** (0.080)
TECHsq		0.119** (0.047)						0.119*** (0.036)	0.0222 (0.019)	0.0988** (0.040)	0.118*** (0.037)	0.138*** (0.040)
Constant	-2.44 (1.567)	-1.672 (1.494)	-2.44 (1.715)	-1.513** (0.748)	-1.112 (1.566)	-2.366 (1.712)	-3.863* (2.156)	-1.672 (1.781)	-1.940** (0.755)	0.0579 (1.633)	-1.618 (1.795)	-3.372 (2.224)
Observations	208	208	208	208	208	208	208	208	208	208	208	208

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

Table 6. JKS multivariate non-causality test- Full Sample.

Full Sample								
	1	2	3	4	5	6	7	8
Variables	CO2	P	GDP	GDPSQ	FOSSIL-IQ	PCA	TECH	TECHSQ
Panel A: Non-causality test								
		39.71***	144.4***	231.459***	154.702***	111.858***	52.639***	63.784***
		0.000	0.000	0.000	0.000	0.000	0.000	0.000
Panel B: -Panel Jackknife estimates of Selected covariates								
P	0.0711 (0.210)		-0.332*** (0.082)	-2.487*** (0.627)	-0.0485 (0.105)	-0.191 (0.844)	-0.301 (0.844)	-0.221 (0.844)
GDP	0.169 (0.752)	-0.0604*** (0.015)		19.68** (8.504)	-2.007*** (0.716)	2.265 (2.445)	1.264 (2.445)	2.001 (2.445)
GDPSQ	-0.0039 (0.092)	0.00993*** (0.002)	-0.192 (0.169)		0.320*** (0.089)	-0.401 (0.304)	-0.101 (0.304)	-0.111 (0.304)
.FOSSIL	0.0145 (0.065)	-0.00399*** (0.001)	0.0261 (0.023)	0.262 (0.183)		0.215 (0.378)	0.315 (0.378)	0.115 (0.378)
PCA-IQ	-0.004 (0.010)	-5.91E-05 (0.000)	-0.00524 (0.004)	-0.035 (0.025)	0.00696 (0.006)		1.017 (1.293)	1.007 (1.293)
TECH	-0.272*** (0.099)	-0.00531* (0.003)	0.0756*** (0.020)	0.590*** (0.135)	-0.176 (0.117)	1.147 (1.293)		-0.418 (0.414)
TECHSQ	0.111*** (0.042)	0.00191 (0.002)	-0.0300*** (0.011)	-0.240*** (0.072)	0.0646 (0.052)	-0.21 (0.414)	-0.21 (0.414)	
CO2		-0.00248 (0.003)	-0.000374 (0.014)	-0.00511 (0.090)	0.283** (0.142)	0.741** (0.357)	0.741** (0.357)	0.741** (0.357)
Observations	16	16	16	16	16	16	16	16

H0: Selected covariates do not Granger-cause; *H1*: *H0* is violated; Standard errors in (); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.4. Robustness test

The Half-Panel Jackknife (HPJ) Wald-type test, developed by Juodis, Karavias, and Sarafidis (2021), is employed to enhance the robustness of the empirical findings. This technique demonstrates superior size and power performance compared to other similar methods found in the literature and is capable of estimating multivariate and heterogeneous panel data models (Xiao et al. 2023). By utilizing the

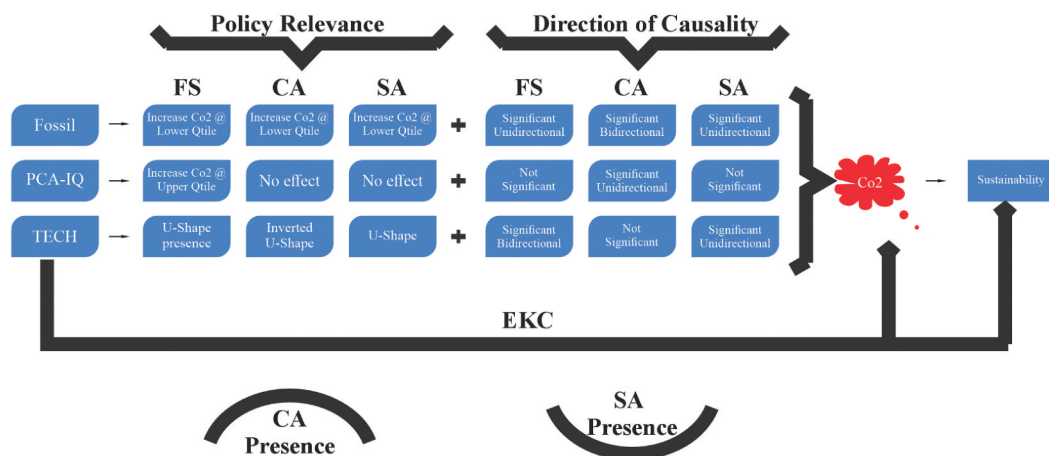


Figure 4. Technological road map to Sustainability. FS = full sample, CA = Central Africa, SA = South Africa.

bootstrap variance option, which accounts for cross-sectional dependence, the test algorithm executes the Wald test to determine the presence of Granger causality. It employs the bias-corrected pooled estimator to elucidate how selected covariates influence the equation, utilizing cross-sectional heteroskedasticity-robust standard errors. The results are presented in [Table 6](#), with a summarized visualization in [Figure 4](#). Columns (1) of the specifications examine whether P, GDP, GDPSQ, FOSSIL, PCA, TECH, and TECHSQ Granger cause CO₂. The HPJ Wald statistic is statistically significant in these specifications, rejecting the null hypothesis that the covariates do not Granger-cause CO₂ in the full sample region. Furthermore, the regression output of the bias-corrected pooled estimator in Panel B indicates that the test outcome of the multivariate equation is significantly influenced by past values of TECH and TECHsq. The coefficient estimates suggest that technology progression has a positive and negative (U-shaped) effect on CO₂ in the full sample. The estimates for other variables in the model are both found to be insignificant. However, there is a unidirectional causality running from CO₂ to FOSSIL and PCA (as seen in column 5 & 6). Another noteworthy finding is the bidirectional positive relationship between TECH and TECHsq (as observed in columns 7 and 8). As illustrated in [Figure S5](#), building capacity vis-à-vis technological progression is a critical step toward environmental sustainability of the region.

To streamline, we concurrently investigate the causal relationships within the sub-sample, commencing with Central Africa. The outcomes are depicted in [Table 7](#), accompanied by a summarized visualization in [Figure S5](#). The evidence is similar to repositories in the case of [Okere et al. \(2022\)](#), [Muoneke, Okere, and Nwaeze \(2022\)](#) and [Okere et al. \(2021\)](#). The first columns of the specifications assess whether P, GDP, GDPSQ, FOSSIL, PCA, TECH, and TECHSQ Granger cause CO₂. The statistically significant HPJ Wald statistic in these specifications rejects the null hypothesis that the covariates do not Granger-cause CO₂ in the entire sub-sample region. Additionally, the regression output from the bias-corrected pooled estimator in Panel B (Central Africa) indicates that the test results of the multivariate equation are notably influenced by past values of GDPsq and FOSSIL. The estimates for other variables in the model are both deemed insignificant. Bidirectional causality is evident, indicating a relationship running from CO₂ to GDPsq and FOSSIL, as observed in columns 4 and 5. There is a one-way causal relationship from fossil fuel to technology (TECH), indicating that greater energy consumption, in this context, may be linked to an increase in the use of fossil fuels. This is especially significant in areas where alternative energy sources facilitated by technology have not been extensively embraced (see column 7). Similarly, in Panel B (South African countries), there is an inverted U-shaped relationship from GDP and GDPsq to CO₂ and a U-shaped relationship from TECH and TECHsq to CO₂. Another noteworthy finding is the bidirectional positive relationship, with an inverted U-shaped connection from CO₂ to GDP and GDPsq as observed in columns 3, 4, and 5.

5. Conclusion and policy implications

This study extends the STIRPAT equation to examine the environmental impact of economic reliance on technological progress, fossil fuels and institutional quality in a selection of Africa economies, with a particular focus on the role of technological progress proxied with medium- and high-technology industries. It utilizes the CO₂ as the sustainability indicator. The empirical analysis relies on a panel dataset spanning from 1996 to 2021 and employs the novel method of moments quantile regression technique, along with the bootstrap variance procedure and FE-DK. The results show that population size and fossil fuel have a significant detrimental effect on the environmental sustainability, while CO₂ increases specifically at the lower quantiles. Institutional quality has no effect on environmental sustainability. The non-significant effect institutional quality on CO₂ emission shows that economic dependence on institutional quality does not transmit to carbon mitigation implying inoperability of anthropogenic channel; the central Africa has witnessed a significant low pace adopting technological path for environmental sustainability. There is U-shaped relationship between technological progress and CO₂ emissions with the threshold level technological progress in South African countries

Table 7. JKS Causality- Central Africa & South Africa.

VAR	Central Africa								South Africa							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
	CO2	P	GDP	GDPsq	FOSSIL	PCA-IQ	TECH	TECHsq	CO2	P	GDP	GDPsq	FOSSIL	PCA-IQ	TECH	TECHsq
Panel A: Non-causality test																
	199.674***	0.000	146.684***	334.602***	963.001***	993.41***	144.66***	54.678***		91.215***	77.802***	77.889***	21.556***	41.001***	33.334***	41.266***
			0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000
Panel B: -JKS estimates																
P	-0.103 (0.256)		-0.446*** (0.090)	-3.348** (0.681)	-0.0641 (0.120)	-0.404 (0.648)	-0.204 (0.148)	-0.104 (0.448)	0.102 (0.188)		-0.0539 (0.042)	-0.648** (0.322)	-0.592*** (0.084)	-3.434** (1.291)	-1.202** (0.211)	-1.426** (1.761)
GDP	-1.130 (0.769)	-0.0795** (0.008)		9.927 (6.356)	-3.045*** (0.311)	7.157** (3.206)	1.157** (5.001)	0.156** (2.211)	3.956** (1.811)	0.0241 (0.034)		54.57*** (2.668)	0.48 (1.091)	11.72** (5.071)	12.727** (4.071)	9.501** (3.051)
GDPsq	0.185** (0.087)	0.0123*** (0.001)	-0.0702 (0.101)		0.461*** (0.039)	-0.986** (0.394)	-0.116* (0.224)	-0.666** (0.114)	-0.541** (0.243)	-0.0028 (0.004)	-1.010*** (0.053)	-0.124 (0.133)	-0.0577 (0.155)	-1.543** (0.695)	-1.103** (0.225)	-1.271** (0.335)
FOSSIL	0.149* (0.087)	-0.0011 (0.001)	0.1000*** (0.021)	0.800*** (0.156)		0.555* (0.323)	0.155* (0.323)	0.225* (0.223)	-0.0988** (0.032)	-0.0067*** (0.002)	-0.0161 (0.020)			-0.657** (0.120)	-0.157** (0.230)	-0.144** (0.220)
PCA-IQ	0.0478** (0.017)	-0.0016** (0.000)	-0.0249** (0.007)	-0.156** (0.041)	-0.0271** (0.003)		-0.107 (0.252)	-0.301 (0.752)	5.27E-05 (0.004)	0.0088*** (0.000)	0.0924*** (0.003)	0.0581*** (0.022)	0.006 (0.005)		1.123 (1.136)	0.122 (1.117)
TECH	-1.013 (1.023)	-11.30*** (0.015)	-0.14 (0.106)	-0.994 (0.779)	-1.067 (0.317)	-0.207 (0.852)		-0.0226 (0.101)	-0.178*** (0.047)	-0.0296 (0.003)	0.0657*** (0.021)	0.571*** (0.141)	-0.0949** (0.027)	2.125 (1.937)		-0.399 (0.201)
TECHsq	0.508 (0.644)	8.271*** (0.009)	0.0912 (0.073)	0.647 (0.534)	0.630*** (0.176)	-0.0426 (0.511)	-0.142 (0.411)		0.0999*** (0.030)	0.0133 (0.002)	-0.0300*** (0.011)	-0.258*** (0.072)	0.0533*** (0.009)	-0.399 (0.610)	-0.299 (0.700)	
CO2		-0.0025 (0.004)	-0.0257 (0.017)	-0.170* (0.102)	0.365** (0.174)	0.221 (0.254)	0.0110 (0.154)	0.3011 (0.354)		-0.0119 (0.003)	0.0142 (0.023)	0.166 (0.150)	0.0649 (0.069)	0.5101 (1.044)	0.441 (0.044)	0.5100 (2.044)
Observ	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8

JKS- Jackknife Selected covariates.

H0: Selected covariates do not Granger-cause; H1: H0 is violated; Standard errors in (); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

estimated to be within the range of 2.6216–2.6557% of TECH. This implies that further advancements in technology is anticipated to contribute positively to carbon neutrality in the region.

Additionally, to confirm the robustness of the empirical findings, we implement a multivariate Granger causality technique in heterogeneous panels. This technique is based on the Half-Panel Jackknife (HPJ) Wald-type test with a bias-corrected pooled estimator. The findings show that, under a multivariate system, the joint predictive power of the impact model is significantly influenced by fossil fuel, institution quality and technological progression. The bias-corrected pooled estimator reported mixed findings in case of Central Africa and Southern Africa; in Central Africa on average, high GDP per capita and fossil fuel consumption have a detrimental effect on environmental sustainability (CO₂) in the region. Furthermore, a bidirectional causal relationship exists between CO₂ and high GDP per capita and fossil fuel consumption, and unidirectional causality exists from fossil fuel to TECH. In summary, the results indicate a mutually positive connection between CO₂ and technology (TECH), and a one-way causality from TECH to fossil fuel. This suggests that technological advancements have the potential to stimulate innovations such as more efficient extraction methods, cleaner combustion processes, or the exploration of alternative energy sources. Implicitly, these innovations offer pathways toward achieving environmental sustainability in the South African region.

The results obtained from the empirical analysis offers beautiful insights to direct policymaking in Central and Southern Africa pertaining technological progress, fossil fuels, institutional quality and environmental sustainability in both regions. The one-way causality running from technology to fossil fuels encourages further investment in fossil fuels which negates the loci of energy transition to aid environmental sustainability. On the other hand, relevant bureaucrats in ministry of environment in both regions should advise their governments to redirect foreign and local-owned investments from fossil fuels to renewable energy and other solid environmental technologies that can assist the reduction of greenhouse gases. Furthermore, foreign and local investments in technologies to increase energy efficiency in agriculture, transport, energy, services, industry, manufacturing (textiles and breweries) will go a long way in reducing the rate of environmental decline in Central Africa and Southern Africa. The absence of strong institutional arrangements will continue to hamper any sound efforts to increase clean environmental technologies investments and adoption to reduce the rate of gases emanating from the reliance on fossil fuels. Asides installing a sound watchdog system to check corruption in both military regimes and democratic dispensations, bureaucrats must be trained to source funds for other renewable energy projects such as biomass, solar and wind energy aside the popular hydro-related power in the region, possess technical skills to plan, regulate, and monitor implementation of renewable energy projects and weed-out barriers and red-tape affecting the adoption of renewable energy in both Central and Southern Africa.

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