Environmental Science and Pollution Research (2022) 29:54122–54135
https://doi.org/10.1007/s11356-022-19340-6

RESEARCH ARTICLE

Towards a sustainable consumption approach: the effect of trade flow and clean energy on consumption-based carbon emissions in the Sub-Saharan African countries

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Received: 5 January 2022 / Accepted: 17 February 2022

Abstract

Environmental degradation has accelerated rapidly in recent decades. Researchers and policymakers around the world have concentrated their efforts on this phenomenon because of its effect on human beings. Because of the expanding desire for fossil fuels in developed and developing nations, there has been minimal worldwide agreement on how energy consumption and carbon emissions can be reduced in recent years. On the other hand, several nations are implementing steps to adhere to the Paris Climate Agreement, which was signed in 2015. Therefore, this research intends to examine the effect of trade, economic growth, natural resources, clean energy, and urbanization on consumption-based carbon emissions (CCO_2) for economies in Sub-Saharan Africa (SSA) from 1990 to 2018. The study employed second-generation techniques including CS-ARDL, which revealed that trade flow, income, natural resources, and urbanization exert a positive impact on CCO_2 emissions. Furthermore, the interaction between trade and income contribute to the increase in CCO_2 emissions. In addition, clean energy impacts CCO_2 emissions negatively. From the causality analysis, it is observed that there is a feedback causality between CCO_2 emissions and income, clean energy, and urbanization, while a one-way causality was detected running from natural resources rent to CCO_2 emission. These outcomes might help policymakers to adopt measures that are eco-friendly such as the utilization of clean energy in order for countries in Sub-Saharan Africa to attain a green environment.

Keywords Consumption-based CO_2 emission · Trade flow · Natural resources · Clean energy · Urbanization · Sub-Saharan African countries

Introduction

The world economy is increasing exponentially by between 3 and 4% per year (Ding et al., 2021). Consequently, there is a significant risk that environmental damage will worsen due to CO_2 pollution resulting from the overuse of fossil energy, thus causing global warming (Bennett & James, 2017). With increased economic operations in both established and emerging economies over the last few years, trade and commerce have seen a significant increase in volume. For example, global trade increased by 62% between 2005 and 2015, and this is only one example. According to the World Bank's 2019 study, the overall contribution of global trade as a proportion of gross domestic product (GDP) reached 58% in 2017, up from 23% in 1960. Indeed, while increased trade flow has generated a plethora of economic advantages, it has also resulted in irreversible environmental

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damage, such as increased CO_2 pollution (Awosusi et al. 2022; Hasanov et al., 2018). From a scholarly perspective, there has been increased focus on the debate surrounding the relationship between trade flow and pollutants. Scholars are examining the trade flow-pollution linkage in the framework of the pollution haven hypothesis (PHH) and carbon leakages. Trade flow is characterized by the movement of contaminating sectors to nations with less strict ecological regulations. Certain wealthy countries have attempted to utilize international trade as a means of decreasing pollution, but this approach has failed as a result of the emissions from the imports and exchange of goods, also known as carbon leakage (Hasanov et al., 2018; Khan et al. 2020a, b, c; Miao et al. 2022b). Moreover, carbon leakages occur when greenhouse gas pollution in one economy increases due to a greenhouse gas output mitigation plan implemented by another economy that has strict environmental targets. As a result, governments worldwide are implementing various eco-innovation approaches, such as clean energy investment, to combat the deteriorating environment. In turn, these tactics help reduce pollution in the long term (Ding et al., 2021).

Meanwhile, SSA suffers from a scarcity of energy. With regard to energy availability, installed capacity, and overall usage, the region's power industry is severely undeveloped compared to other parts of the world. Energy security in Sub-Saharan African households and commercial sectors make it challenging for countries in the region to continue economic growth. The consequences are severe. Furthermore, the willingness of authorities and investors to expand the continent's immense energy resources is critical to the region.

Energy output measures the eco-measures achieved from each unit of energy utilized. It is calculated by dividing gross production or economic productivity (e.g., income or GDP) by the overall energy intake (e.g., kilowatt-hours of electricity or barrels of oil equivalent). The concept of energy output and energy intensity is distinct from each other. Essentially, the first is equivalent to GDP per unit of the primary energy mix. In contrast, the latter equals the energy required to produce one unit of output. Energy output contributes to improved ecological integrity by increasing energy performance and lowering the cost of energy (Huaman & Jun, 2014). A rise in energy efficiency results in a reasonably high level of economic activity at the expense of reducing overall energy usage. There are three mechanisms through which energy efficiency influences CO_2 pollution. Firstly, a rise in energy productivity decreases the amount of energy utilized per output unit produced. Second, increased energy efficiency contributes to lower energy expenses. Third, increased energy production contributes to a decrease in oil imports, which reduces greenhouse gas pollution. As a result, increasing energy production remains a primary goal in attaining ecological expansion (Choi and Yu 2017). The assessment of energy output growth permits governments to evaluate the efficiency of their energy resource use. Internationally, policymakers' attention is focused on energy utilization to analyze the prices and advantages of engaging in energy-connected technology. In the USA, policymakers are focusing on energy efficacy. As a result, focusing on energy utilization is critical in terms of recognizing the significance of energy consumption that is both efficient and effective (Bean, 2014).

Although analysis by Shahbaz (2013) as well as Yang et al. (2020) examined the impact of production or territory-based carbon pollution (PCO_2), they did not consider the multi-national product development procedure. In this research, CCO_2 emissions were not considered, even after accounting for trade flow (imports and exports). CCO_2 and PCO_2 are the two methods utilized to compute emissions. The usual metric of carbon emissions is PCO_2, which does not consider imports and exports. A new CCO_2 databank has been constructed, which is computed as the sum of PCO_2 + imports minus exports plus other sources of pollution (Peters et al., 2011). Researchers have discovered that the results of analyses depend on two different carbon emissions methodologies for industrialized and emerging nations (Knight & Schor, 2014; Liddle 2018 and Khan et al., 2020a, b, c).

Moreover, the main purpose of this study is to investigate the influence of trade flow, energy intake, and natural resources on CCO_2 for SSA counties in order to address ecological and economic difficulties as most developed nations have turned to energy productivity and renewable energies. Approximately 770,000 people die each year on the African continent alone as a result of air pollution, which includes carbon pollution. Furthermore, over 40,000 people die each year as a consequence of pollution caused by biomass gasification greenhouse gases, food yield leftovers, land gas, litter, and alcoholic beverages (Bauer et al. 2019). Since industrial activities account for more than 30% of the world's energy consumption and produce 20% of global CO_2 pollution that is harmful to human health, industrial economies are at risk of producing even more CO_2 in the future (Sarpong and Bein, 2020). As African countries seek to modernize their economies, the continent's ecosystems are likewise at risk of degrading in quality. Although global warming and its detrimental consequences on humans and nature have received considerable attention, a number of researchers have concentrated on measures to minimize these impacts.

Therefore, this study aims to examine the effect of trade flow, income, clean energy, natural resources, and urbanization on consumption-based carbon emissions (CCO_2) for the Sub-Saharan African countries, which have gained minimal attention in the literature (Gyamfi 2021). Moreover, the causal connection between CCO_2 emissions, trade flow, income, clean energy, natural resources, and urbanization is also examined. However, the moderating role of trade flow and income is examined in the income-CO_2 emission relationship for the Sub-Saharan African countries. Again, the study employs a novel technique to access the relationship among the coefficients. The Pesaran (2015) LM test, the Pesaran (2007) CD test, and the Breusch and Pagan (1980) LM test are used to evaluate cross-sectional dependence, while the Pesaran (2007) panel root unit test is used to investigate the integration characteristics of the coefficients. Following that, the analysis uses the Westerlund (2007) test to examine the long-run stable connection between the factors that have been emphasized. To access the long-run connection among the variables, the CS-ARDL technique, which outperforms other techniques in many ways, is utilized. Firstly, it can be employed even if there is a problem with non-stationarity or a varied order of integration. Secondly, this technique takes into account cross-sectional dependence and heterogeneity issues.

The next section presents the summary of the literature. The "Theoretical underpinnings, data, and methodology" section presents the data and methodology. The "Findings and discussion" section presents findings and discussion. The last section presents conclusion and recommendations.

Literature review

Clean energy and CCO_2 emissions relationship

Clean energy is becoming more popular throughout the world due to issues of environmental degradation. As a result, Adebayo and Rjoub (2021) used Westerlund cointegration, cross-sectional augmented autoregressive distributed lag (CS-ARDL) and augmented mean group (AMG) tests to simulate the relationship between clean energy and CCO_2 pollution from 1990 to 2017 in Mexico, Indonesia, Nigeria, and Turkey (MINT nations). The authors of this study argued that the usage of clean energy contributes to a decrease in CCO_2 emissions. Using second-generation panel cointegration approaches, Khan et al. (2020a) analyzed the impact of clean energy on CCO_2 emissions from 1990 to 2017. The results indicated that reducing CCO_2 emissions can be accomplished by using clean energy sources. In a similar vein, Khan et al. (2020b) found that clean energy has a considerable impact on reducing CCO_2 emissions. Econometric estimations were used to analyze the link between clean energy and CCO_2 emissions using data from 1990 to 2017 in China. In contrast, the empirical findings using data of G7 countries from 1990 to 2018 revealed that clean energy is one of the primary factors that contribute to CCO_2 emissions (Ding et al., 2021). Hanif (2018) also reported that clean energy has a positive impact on CCO2 emissions. Generalized method of moments (GMM) was used in the study to analyze a panel of 25 upper and lower-middle income countries from 1990 to 2015.

Kirikkaleli and Adebayo (2021) studied the effect of clean energy intake on CCO_2 pollution from 1990 to 2015 in India. The findings showed that investments in clean energy reduce CCO_2 emissions over the long term. Using data from E-7countries, Hussain et al. (2020) looked at the connection regarding clean energy intake and CCO_2 pollution for the period of 1990–2016. The result from the study indicated that usage of clean energy simulates a reduction in CCO2 emissions. A similar outcome is reported in Kirikkaleli et al. (2021) study in Chile. Research showed that Chile's CCO_2 emissions may be reduced via the use of clean energy. Ali and Kirikkaleli (2021a, b) also found substantial correlations between clean energy and CCO_2 emissions using data for Italy from 1970 to 2018. The findings showed that employing clean energy reduces CCO_2 emissions which could contribute in attaining a greener future. Research by Zhang et al. (2020) examined the energy intake of BRI nations starting 1995–2015. According to the findings, clean energy decreases CO_2 emissions in the 56 BRI nations.

Economic growth and CCO_2 relationship

Research on CCO_2 emissions has taken into account the enormous impact of economic growth. He et al. (2021) analyzed the case of Mexico using a dataset covering the period from 1990 to 2018. The findings revealed that economic growth predicts CCO_2 emissions which could be detrimental to the quality of the environment. Iqbal and Nosheen (2021) studied factors influencing CCO_2 emissions in MINT nations from 1990 to 2018. Nonlinear ARDL technique was utilized to examine the relationships between the variables in the research. The examined results specified a correlation between economic growth and CCO_2 in Africa. Using ARDL bounds, DOLS, and gradual shift causality tests, Adebayo, Adebayo and Kirikkaleli (2021) studied the impact of economic development on Brazil's CCO_2 emissions between the periods of 1990 to 2018. According to the findings, economic growth in Brazil increases CCO_2 emissions giving rise to environmental degradation.

Safi et al. (2021) used second- and third-generation panel cointegration methodologies to examine the effect of economic growth on CCO_2 emission of E-7 countries from 1995 to 2018. The findings indicated that economic growth increases CO_2 in the short and long run. Zhang et al. (2014) utilized a multi-regional input–output model to examine the differences in CCO_2 emissions from China provinces between 2002 and 2007. According to the study's findings, China's CCO_2 emissions increased as a consequence of economic expansion in several Chinese regions. A similar outcome is attained from Hasanov et al. (2018) study which examined the impact of economic development on CCO_2 emissions in nine oil exporting countries during 1995–2013, utilizing a cointegration and error correction model.

Natural resources and CCO_2 relationship

Environmental sustainability is impossible without prudent use of natural resources, and more environmental damage is imminent with an increase in $CC0_2$ emissions (Zhang et al., 2018). Kwakwa et al. (2020) investigated the long-run and short-run effects of natural resource exploitation on CCO_2 emissions in Ghana. According to the findings, $CC0_2$ emissions are influenced by the country's natural resources.

The relationship between the volatility of carbon emissions and the usage of NR is examined by Yu-Ke et al. (2021). The paper delves at panel data from the G-20 nations between 1995 and 2018. The study argued that G-20 nations' carbon emissions were reduced significantly by the rents on mineral resources, oil resources, and forest resources. Results found that NR had a significant influence on CO_2 emissions and that the large extraction of oil, gas, minerals, and forest resources is not only boosting CO_2 pollution but also depleting and destroying the natural environment.

Baloch et al. (2019) examined the impact of natural resources on $CC0_2$ emissions in BRICS nations using yearly panel data covering 1990–2015. By using the augmented mean group (AMG) panel method, result found the diverse influence of natural resources on CCO_2 emissions across the BRICS nations. According to the findings, natural resources reduce CCO_2 emissions in Russia but add to pollution in South Africa. However, natural resource endowment had a considerable impact on CCO_2 emissions in host countries (Li et al. 2019). An empirical finding using the Granger causality analysis found evidence that the G7 nations' consumption of fossil fuels had a significant impact on CCO_2 emissions (Gyamfi et al., 2021a, b). This confirms the arguments that natural resource revenues are mostly used to expand production, which increases environmental damage.

Trade flow and CCO_2 relationship

It is assumed that trade flow has a connection to environmental degradation. In the host country, trade is a significant contributor to the emission of $CC0_2$. There has been a slew of research looking at the link between trade and carbon dioxide emissions. For example, Ali and Kirikkaleli (2021a, 2021b) used the Gregory–Hansen model to examine the asymmetric influence of trade flow on CCO2 emissions in Italy. Results showed that increased trade flow has a significant impact on CCO_2 emissions, indicating that rising trade flow is linked to a decrease in $CC0_2$ emissions. Similar findings were discovered in Shekhawat et al. (2021) study on the determinants of consumption-based CCO_2 emissions in SAARC countries from 1990 to 2018. The research, in particular, investigates the connection between CCO2 emissions and trade by utilizing traditional and second-generation panel cointegration approaches. The findings show that trade flow decreases CCO_2 emissions over the long term. The analysis rejects the "pollution-haven theory" for the SAARC area based on the conclusion of trade flow.

Hassan et al. (2021) and Khan et al. (2020a, b, c) found that trade flow is a significant source of CCO_2 emission. A study by Tsagkari et al. (2018) showed that trade flow decreases $CC0_2$ emissions. On the other hand, Liddle (2018a) estimate the environmental benefits of trade flow on $CC0_2$ emissions. Nonetheless, Liddle (2018b) demonstrated that trade flow is correlated with increased $CC0_2$ emissions in 20 Asian countries. Adebayo et al. (2021b) examined the asymmetric effect of trade on CCO_2 in MINT countries between 1990 and 2018. The findings of the study show that CCO_2 emissions are predicted by trade.

This study adds to the expanding body of knowledge on environmental degradation in a variety of ways: The first distinction of this research is that it employs the newly generated consumption-based carbon emissions (CCO_2 emissions) metric, which estimates emissions based on trade flow, clean energy, natural resources, and economic growth. An effective strategy for combating pollution and climate change requires appropriate findings on CCO_2. The second unique aspect of this research is that it considers the impact of clean energy consumption on CCO_2 emissions in Sub-Saharan African countries. Moreover, to the best of the author's understanding, this point indicates that this is the first attempt to investigate the influence of trade flow on CCO_2 emissions for the SSA group of nations over the period 1990–2018. Furthermore, this study employs

Table 1 Description of variables

Name of Indicator	Abbreviation	Proxy/Scale of Measurement	Source
Consumption-Based CO_2 Emissions	CCO_2	Metric tons per capita	Friedlingstein et al. (2019)
Income	Y	GDP per capita (2010 Constant USD)	WDI
Clean energy	CE	% of total final energy consumption	BP
Natural resources	NR	Total natural resource rent (% of GDP	WDI
Trade liberalization	TRL	Import + Export	WDI
Urban population	UB	(% of total population)	WDI
Income*Trade liberalization	Y*TRL	Interaction term	WDI

sophisticated econometric approaches to examine the unit root test, cointegration, and short- and long-run estimates. For instance, the CS-ARDL model is employed in this work to determine the short- and long-run connection between the variables.

Theoretical underpinning, data, and methodology

Theoretical underpinning and data

Recently, studies on analyzing drivers of environmental deterioration are rising (Li et al. 2020; An et al. 2019; Wang and Lu 2022; Miao et al. 2022a). In this empirical analysis, we aim to assess the effect of trade liberalization as well as clean energy on CCO_2 emissions for the case of the SSA nations. Furthermore, we incorporate other determinants of CCO_2 emissions such as urbanization and natural resources into the model. The dependent coefficient is CCO_2 emissions, while the regressors are trade liberalization, clean energy, economic growth, natural resources, and urbanization. The dataset for CCO_2 is gathered from Friedlingstein et al. (2019), and it is measured as metric tons per capita. Economic growth is calculated as GDP per capita, urbanization is calculated as urban population (% of population), clean energy is calculated as % of total final energy consumption, economic globalization is measured as the economic globalization index, trade liberalization is measured as imports plus exports, and natural resource is measured as resource rent % of GDP. Moreover, economic growth, natural resource, and urbanization are sourced from the World Bank database, while clean energy is obtained from the British Petroleum database. Table 1 presents the sources and units of the variables' measurements. Furthermore, the current research transforms all the variables of investigation into log form to ensure they align with normal distribution (Oladipupo et al. 2021; Adebayo & Kirikkaleli 2021).

The current research follows the research conducted by Kirikkaleli and Adebayo (2021) in India. However, the current research compliment their research by adding economic globalization and trade liberalization into the model. The study's economic function is present in Eq. 1 as follows:

$$CCO_{2i,t} = \beta_0 + \beta_1 Y_{i,t} + \beta_2 CE_{i,t} + \beta_3 NR_{i,t} + \beta_4 TRL_{i,t} + \beta_5 UB_{i,t} + \varepsilon_{i,t} \tag{1}$$

where CCO_2, Y, EG, CE, NR, TRL, and UB stands for CCO_2 emissions, income, economic globalization, natural resource, trade liberalization, and urbanization, respectively. Furthermore, t, i, and ε represent timeframe, cross-section, i.e. sub-Sahara nations, and error term, respectively. Furthermore, we assess the joint effect of trade liberalization and income on CCO_2 emissions. This idea is illustrated in Eq. 2 as follows:

$$CCO_{2i,t} = \beta_0 + \beta_1 Y_{i,t} + \beta_2 CE_{i,t} + \beta_3 NR_{i,t} + \beta_4 TRL_{i,t} + \beta_5 UB_{i,t} + \beta_6 Y * TRL_{i,t} + \varepsilon_{i,t} \tag{2}$$

where the interaction term is denoted by Y $*$ TRL. The remaining indicators are the same as Eq. 1.

The rationale of using the variables discussed above in this empirical research is indicated below. Countless studies on these relationships have been undertaken over the years (Akadiri et al. 2021; Usman et al. 2021; Arshian et al. 2021; Shahbaz et al. 2018; Alola et al. 2021). Unfortunately, none of these researchers consider CCO_2 emissions in their research. CCO_2 emissions is critical, according to Güngör et al. (2021), since it not only considers the world's supply chain, but also adds to the establishment of pollutants and separates regarding pollutants generated in one nation and pollutants consumed in another. We incorporate Y into the research framework in line with the works of Gyamfi et al. (2021a, b) and Bekun et al. (2021). The current paper uses Sub-Saharan African nations as a case study which are developing nations. It is well established in empirical studies that developing nations favor constant growth over environmental safety. Therefore, Y and CCO_2 are projected to have a positive interrelationship. This shows an increment in GDP would degrade environmental quality, i.e., $\left(\beta_1 = \frac{\theta CCO_2}{\theta Y} > 0\right)$. Furthermore, we incorporate economic globalization into the framework in line with Kirikkaleli et al. (2021) and He et al. (2021) studies. Likewise, CE is introduced into the model following the studies of Sarkodie et al. (2021) and Gyamfi et al. (2021a, b). Renewable energy use is anticipated to lessen CCO_2 emissions as a result; the interconnection between CE and CCO_2 is expected to be negative, i.e., $\left(\beta_2 = \frac{\theta CCO_2}{\theta CE} < 0\right)$. Following the works of Akadiri et al. (2021) and Tufail et al. (2021), NR was inputted into the model and the association with CCO_2 emissions is expected to be positive, i.e., $\left(\beta_3 = \frac{\theta CCO_2}{\theta NR} > 0\right)$. Trade liberation effect on CCO_2 mixed. For instance, the effect of TRL is expected to be positive, i.e., $\left(\beta_4 = \frac{\theta CCO_2}{\theta TRL} > 0\right)$ if the nations are still at the effect stage, while the effect is expected to be negative, i.e., $\left(\beta_4 = \frac{\theta CCO_2}{\theta TRL} < 0\right)$ if the nations are at the technique and composite stages. Moreover, we incorporate urbanization into the framework following Zhang et al. (2021) and Odugbesan et al. (2021) studies. The UB effect on CCO_2 in the sub-Sahara nations is anticipated to be positive, i.e., $\left(\beta_5 = \frac{\theta CCO_2}{\theta UB} > 0\right)$. Lastly, we assessed the joint effect of Y*TRL on CCO_2 emissions. The effect is anticipated to be negative, i.e., $\left(\beta_6 = \frac{\theta CCO_2}{\theta Y*TRL} < 0\right)$ if it is ecofriendly and $\left(\beta_6 = \frac{\theta CCO_2}{\theta Y*TRL} > 0\right)$ if not ecofriendly.

Methodology

Cross-sectional dependence and slope heterogeneity tests

With more worldwide globalization and less trade restrictions, cross-sectional dependency (CD) in panel regression is more probable to appear in the contemporary period. Ignoring the CD dilemma and asserting CD can result to estimates that are erroneous, biased, and incorrect. The Pesaran (2015) test is used to determine CD in this research. Similarly, assuming a homogeneous slope coefficient without evaluating for heterogeneity might result in misleading estimator results. As a consequence, Pesaran and Yamagata (2008) developed an improved version of Swamy's (1970) slope heterogeneity test (SH). It is crucial to check for the presence of CD and SH before obtaining the stationarity properties of variables. The following are the SH test equations:

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - k\right) \tag{3}$$

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S} - 2k\right) \tag{4}$$

where delta tilde and adjusted delta tilde are shown by $\tilde{\Delta}_{SH}$ and $\tilde{\Delta}_{ASH}$.

Panel unit root tests

The next stage, we assess the unit root properties of the variables. Therefore, the current paper relies on Pesaran (2007)'s cross-sectional augmented IPS and ADF tests, which are also known as the CADF and CIPS tests. The CADF test equation looks like this;

$$\Delta Y_{i,t} = \gamma_i + \gamma_i Y_{i,t-1} + \gamma_i \overline{X}_{t-1} + \sum_{l=0}^{p} \gamma_{il} \Delta \overline{Y_{t-l}} + \sum_{l=1}^{p} \gamma_{il} \Delta Y_{i,t-l} + \varepsilon_{it} \tag{5}$$

where $\Delta\overline{Y_{t-l}}$ and $\overline{Y}_{t-1}$ represent the first differences and lagged averages. Equation 6 also displays the CIPS test statistic calculated by averaging each CADF.

$$\widehat{\mathrm{CIPS}} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{CADF_i} \tag{6}$$

Equation 6 produces the CIPS, which is derived from Eq. 5. Since the 1st-generation unit root tests generate inconsistent results, especially when there is CD in the data, these 2nd-generation unit root tests have lately been employed.

Panel cointegration test

The current paper uses the Westerlund (2007) cointegration test to capture the long-run interconnectedness between CCO2 emissions and the independent variables. Unlike the first-generation cointegration, this technique takes into account CD and slope heterogeneity. The test is depicted as follows:

$$\alpha i(L)\Delta y_{it} = y2_{it} + \beta_i\left(y_{it} - 1 - \alpha_i \mathrm{x_{it}}\right) + \lambda_\mathrm{i}(\mathrm{L})\mathrm{v_{it}} + \eta_\mathrm{i} \tag{7}$$

where $\delta_{1i} = \beta_i(1)\widehat{\vartheta}_{21} - \beta_i\lambda_{1i} + \beta_i\widehat{\vartheta}2_i \text{and} y2_i = -\beta_i\lambda 2_i$

The following are the test statistics for the Westerlund cointegration:

$$G_t = \frac{1}{N}\sum_{i-1}^{N} \frac{\acute{\alpha}_i}{SE(\alpha_i)} \tag{8}$$

$$G_\alpha = \frac{1}{N}\sum_{i-1}^{N} \frac{T\alpha_i}{\alpha_i(1)} \tag{9}$$

Table 2 Descriptive statistics and correlation matrix analysis.

	LCCO₂	LTRL	LY	LCE	LNR	LUB	LY*LTRL
Mean	-0.6865	0.4245	7.2640	3.6640	3.2578	10.2197	3.3443
Median	-0.8862	0.6333	7.1713	4.3193	3.2102	14.2174	4.5091
Maximum	2.3023	4.6379	9.3980	4.5823	4.6049	18.3212	43.5881
Minimum	-4.7725	-13.1212	5.1019	-2.8309	0.8086	2.5353	-106.2193
Std. Dev.	1.3304	1.7965	0.9409	1.4411	0.9255	6.3569	13.5691
Skewness	0.2674	-2.9401	0.2296	-2.2133	-0.1795	-0.1416	-3.0368
Kurtosis	2.4422	20.6677	2.9029	7.3697	2.3086	1.0837	24.5059
Jarque-Bera	14.7817*	8581.496*	5.4541***	957.5888*	15.0226*	92.8684*	12360.06*
Probability	(0.0006)	(0.0000)	(0.0654)	(0.0000)	(0.0005)	(0.0000)	(0.0000)
Observations	594	594	594	594	594	594	594
LCCO₂	1						
LTRL	0.0896**	1					
LY	0.9014*	0.1543*	1				
LCE	-0.6970*	0.0774***	-0.5519*	1			
LNR	0.8305*	0.0355*	0.7347*	-0.7226*	1		
LUB	0.6098*	0.0740*	0.7027*	-0.4650*	0.6204**	1	
LY*LTRL	0.1260*	0.9901*	0.1969*	0.0606*	0.0564*	0.0962*	1

$* < 0.01$, $** < 0.05$, $*** < 0.10$.

$$P_T = \frac{\alpha}{SE(\alpha)} \tag{10}$$

$$P_\alpha = T\alpha \tag{11}$$

The group means statistics, comprising G_a and G_t, are shown in Eqs. 7 and 8. Panel statistics, comprising P_a and P_t, are represented by Eqs. 9 and 10.

Cross-section augmented auto-regressive distributed lags (CS-ARDL) test

The CS-ARDL test, introduced by Chudik and Pesaran (2016), is utilized in this work for both long- and short-run evaluations. This test is more efficient and robust than other procedures such as mean group (MG), pooled mean group (PMG), common correlated effect mean group (CCMG), and augmented mean group (AMG) (Wang et al. 2021). The problems of unobserved common components, SH, CD, non-stationarity (mixed order integration), and endogeneity are all addressed by this technique. This is because ignoring unobserved common components will result in erroneous estimation results. The following Equation is a representation of the CS-ARDL:

$$Y_{it} = \sum_{i=1}^{py} \pi_{it} Y_{i,t} + \sum_{i=0}^{pz} \theta_{i1}^{\iota} Z_{i,t-1} + \sum_{i=0}^{pT} \phi_{i1}^{\iota} Z_{i,t-1} + e_{it} \tag{12}$$

where $X_{\underline{t-1}}^{-} = \left(Y_{\underline{t=}1}^{-}, Z_{t-1^{\iota}}^{-} \right)\iota$, average cross-sections are illustrated by Y_t and Z_t. Moreover, X_{t-1}^{-} stand for the averages of both regressors and dependent variable. The coefficients of the mean group and long-run are illustrated as follows in Eqs. 13 and 14.:

$$\widehat{\vartheta}_{\text{CS-ARDL},i} = \frac{\sum_{i=0}^{pz} \widehat{\theta}_{iI}^{\iota}}{1 - \sum_{I=1}^{py} \widehat{\pi}_{iI}} \tag{13}$$

$$\widehat{\vartheta}_{\text{meangroup(MG)}} = \frac{1}{N} \sum_{i=1}^{N} \widehat{\vartheta}_i \tag{14}$$

The current paper also utilizes the FMOLS, DOL, and the AMG approaches as a robustness check for the CS-ARDL long-run association. Furthermore, we utilized the Dumitrescu and Hurlin (2012) causality technique to identify the causal interrelationship among CCO_2 emission sand regressors.

Findings and discussion

Preliminary tests outcomes

This section addresses the outcome of the analysis along with a discussion of the study. From the descriptive analysis presented in Table 2, it can be observed that all the coefficients are skewed negatively except for energy CCO_2 and income, which have positive skewness. Moreover, the correlation matrix revealed a positive significant connection from all the coefficients except for clean energy, which has a negative significant connection

Table 3 Cross-sectional dependency (CD) and slope homogeneity (*SH*) examinations

Model	Pesaran CD test	*p*-value	Pesaran LM test	*p*-value	Breusch-Pagan LM	*p*-value
$LCCO_2$	19.7712*	(0.0000)	82.2714*	(0.0000)	2021.359*	(0.0000)
LTRL	16.0936*	(0.0000)	19.5013*	(0.0000)	672.1656*	(0.0000)
LY	30.6411*	(0.0000)	138.0446*	(0.0000)	3220.156*	(0.0000)
LCE	19.8048*	(0.0000)	84.7251*	(0.0000)	2074.098*	(0.0000)
LNR	11.90023*	(0.0000)	76.2433*	(0.0000)	1891.788*	(0.0000)
LUB	70.5593*	(0.0000)	231.2570*	(0.0000)	5223.682*	(0.0000)
LY*LTRL	16.4540*	(0.0000)	20.1156*	(0.0000)	685.3685*	(0.0000)
Slope homogeneity (**SH**)						
	COEFFICIENT	*p*-value				
SH ($\tilde{\Delta}$ test)	6.7650*	(0.0020)				
SH ($\tilde{\Delta}$ adj test)	7.1591*	(0.0000)				

*<0.01.

Table 4 Panel IPS and CIPS unit root test

Variables	CIPS				IPS			
	I (0)		I (1)		I (0)		I (1)	
	C	C&T	C	C&T	C	C&T	C	C&T
$LCCO_2$	−1.956	−2.918	−5.349*	−5.467*	−1.185	−2.314	−5.306*	−5.225*
LTRL	−1.720	−1.957	−5.736*	−5.854*	1.783	−1.239	−2.661*	−3.348*
LY	−1.513	−1.829	−4.000*	−4.145*	1.423	1.159	−4.896*	−4.193*
LCE	−2.021	−2.681	−4.950*	−4.818*	−1.187	−1.272	−4.529*	−4.759*
LNR	−2.445	−2.807	−5.227*	−5.270*	−1.578	−1.824	−4.262*	−4.555*
LUB	−1.433	−1.297	−5.104*	−5.048*	−1.036	−1.620	−4.346*	−4.293*
LY*LTRL	−1.473	−1.480	−5.691*	−5.880*	−1.438	−1.261	−5.302*	−5.305*

*<0.01, **<0.05, ***<0.10 significance level, respectively, while *C* constant and *C&T* constant and trend.

Table 5 Westerlund cointegration test

Statistics	Value	*p*-value
Gτ	−3.173*	(0.007)
Gα	−7.893*	(0.000)
Pτ	−6.544*	(0.000)
Pα	−11.261*	(0.000)

*<0.01.

with the dependent variable consumption-based carbon emissions.

Again, individual time series are examined first for cross-sectional dependence utilizing the Breusch-Pagan LM test, the Pesaran scaled LM test, and the Pesaran CD test, the results of which are shown in Table 3. It is demonstrated by the cross-sectional association analysis that the null assumption of no cross-sectional connection is rejected for all three procedures tested at the 1% level of significance. Furthermore, the Pesaran and Yamagata (2008) SH test is also significant at 1%. This means that in each of the Sub-Saharan African countries, a shock appears to be conveyed to other states within the panel. The results continue to prove the absence of multicollinearity as well as serial autocorrelation among the dataset. Hence, the CADF and CIPS unit root tests of Pesaran (2007) are reported (in Table 4) to support this conclusion for the variables in the study, and the panel cointegration report is shown in Table 5. The unit root results with regard to CIPS and CADF in Table 4 affirm that the factors are stationary at first difference.

Cointegration outcomes

Furthermore, the results of the Westerlund (2007) cointegration evaluation, as shown in Table 4, indicate that there is a long-term connection between the variables of investigation. Affirmation for this conclusion was provided by evidence rejecting the null assumption, which was established by examining the significance of both the group statistics and the panel statistics found. As a result, the relevant panel approaches were used to obtain the long-run cointegrating factors.

Table 6 CS-ARDL technique

Variables	Coefficient	Std. error	*p*-value
LTRL	0.2243***	[0.1250]	(0.0735)
LY	0.8066*	[0.0465]	(0.0000)
LCE	−0.1274*	[0.0436]	(0.0037)
LNR	0.1094**	[0.0697]	(0.0174)
LUB	0.3251*	[0.0614]	(0.0000)
LY*LTRL	0.0253*	[0.0154]	(0.0029)
F-STAT	0.1543*		(0.0001)
Short run			
ECM	−0.3188*	[0.0872]	(0.0003)
D(LTRL)	0.5133	[0.0147]	(0.6132)
D(LY)	0.3043**	[0.2454]	(0.0156)
D(LCE)	−2.0016**	[0.2692]	(0.0156)
D(LNR)	0.9540	[0.5337]	(0.7067)
D(LUB)	−17.147	[0.2985]	(0.1980)
D(LY*LTRL)	−0.0784	[0.1376]	(0.5689)

*<0.01, **<0.05, ***<0.10, [] for standard error, () for *p*-value, D for short-run coefficients, optimal lags for CS-ARDL by using AIC.

CS-ARDL outcomes

Table 6 shows both the long- and short-run outcomes based on the second-generational CS-ARDL technique employed for this analysis. The analysis shows that clean energy and urbanization have a negative effect on consumption-based carbon, while trade flow, income, natural resources, trade flow and income also increase consumption-based carbon emissions in the long run.

To be specific, the outcomes from the analysis presented in Table 6 reveal that a percentage rise in trade flow reduces CCO_2 by an average of 0.22% in the long run. The flow of trade has resulted in increased CCO_2 pollution in the economies of Sub-Saharan Africa. This has largely happened as result of a rise in the importation of services and goods into the housing and food industries. These consumption habits are frequently related to the acidification of the oceans, climate change, and the extinction of wildlife species. This supports the findings from the World Integrated Trade Solution (WITS) that about 37.49% of imported goods and services into the bloc are consumption goods.[1] However, according to Wiedmann et al. (2007) and Wiedmann (2009), pollutants associated with imported commodities are frequently moved (exported) from advanced markets to emerging markets for consumption in the home country. Davis and Caldeira (2010) discovered that trade was responsible for approximately 23% of all CO_2 emissions globally, based on an analysis of CO_2 emissions and trade statistics (2004). Moreover, the outcomes of this study affirmed the findings of Adebayo et al. (2021), Khan et al (2020a, b, c), Safi et al (2021), and Ding et al (2021).

However, the outcomes show that income increases emissions from CCO_2 in the long run for the Sub-Saharan African countries. Expansion in economic activity results in an average 0.81% rise in consumption-based carbon pollution over the long term. The positive impact is responsible for the rise in economic activity, which puts stress on energy needs and contributes to a rise in energy usage, thus increasing emissions. Furthermore, a rapid escalation in economic activity has resulted in a sudden expansion in the volume greenhouse gases, posing a threat to the long-term viability of life on the planet. As a result, as economic expansion accelerates, CCO_2 pollution rises in tandem. These results are also confirmed by the conclusions of Zhang and Da (2015), Umar et al. (2020), and Dong et al. (2020).

Again, a percentage rise in clean energy decreases CCO_2 pollution by 0.127% in the long run. This outcome affirms the findings of Khan et al (2020a, b, c). Given that clean energy technology makes use of the purest and greenest forms of energy that are both durable and meet the demands of both the present and the future, it is an effective means of reducing CCO_2.

Nevertheless, natural rent has a positive impact on CCO_2 for the SSA nations. This outcome affirms those of Gyamfi (2021) and Ahmad et al. (2020). It can be seen that these countries have a significant level of income that may be used for both export and domestic consumption. This outcome, on the other hand, confirms the notion that the exploitation of natural resources within such countries has never been profitable. Excessive reliance on natural resources results in the degradation of bio-capacity, which is a consequence of the fact that resources cannot be replenished. Some countries also use their natural resources (coal, petroleum, and natural gas) to meet their energy needs, which is a positive development. It has been claimed that the allocation of funds could help a nation to become more self-sufficient by reducing the need for foreign energy imports and increasing the reliance on domestic energy generation with lesser emissions (Ahmed et al. 2020).

Urbanization, on the other hand, also has a positive connection with CCO_2 in the long run for the SSA nations. This supports the findings of Salahuddin et al. (2019) and Gyamfi et al (2021a, b). Urbanization helps to stimulate the economy by increasing the population of municipalities that have limited resources. Nevertheless, urbanization increases the demand for transportation, lodging, household equipment, and other necessities of daily life (Lin and Du 2015). Lastly, the interaction

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[1] https://wits.worldbank.org/countrysnapshot/en/SSF

Table 7 Sensitivity check with AMG, FMOLS, and DOLS

Variables	AMG		FMOLS		DOLS	
	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value
LTRL	0.0291**	(0.0230)	0.0762**	(0.0118)	0.1566*	(0.0060)
LY	0.74955*	(0.0000)	0.6704*	(0.0000)	0.7094*	(0.0000)
LCE	−0.1008***	(0.0510)	−0.0305**	(0.0245)	−0.4415**	(0.0124)
LNR	0.4357*	(0.0000)	0.4465*	(0.0000)	0.4030*	(0.0001)
LUB	0.0166*	(0.0010)	0.2366*	(0.0022)	0.2064**	(0.0253)
LY*LTRL	0.0056***	(0.0590)	0.0128**	(0.0162)	0.0250**	(0.0273)
Wald test	804.03*	(0.0000)				
R^2			0.9733		0.9984	
ADJ R^2			0.9720		0.9920	

* < 0.01, ** < 0.05, *** < 0.10.

Table 8 Dumitrescu and Hurlin (2012) causality Outcomes.

	W-stat	Zbar-stat	*p*-value	Conclusion
LTRL→LCCO$_2$	2.2622	0.0754	(0.9398)	No causality
LCCO$_2$→LTRL	2.6665	0.8389	(0.4015)	
LY→LCCO$_2$	6.1802*	7.4721	(8.E−140)	Feedback causality
LCCO$_2$→LY	7.6187*	10.187	(0.00000	
LCE→LCCO$_2$	3.9184*	3.2022	(0.0014)	Feedback causality
LCCO$_2$→LCE	4.4029*	4.1169	(4.E−05)	
LNR→LCCO$_2$	4.0609*	3.4711	(0.0005)	Unidirectional causality
LCCO$_2$→LNR	2.9797	1.4301	(0.1527)	
LUB→LCCO$_2$	6.4672*	8.0139	(1.E−15)	Feedback causality
LCCO$_2$→LUB	6.2155*	7.5389	(5.E−14)	
LY*LTRL→LCCO$_2$	2.3221	0.1885	(0.8504)	No causality
LCCO$_2$→LY*LTRL	2.6248	0.7600	(0.4472)	

* < 0.01, ** < 0.05, *** < 0.10.

between trade flow and income also has a positive connection with CCO$_2$, implying that a percentage rise in the interaction between trade flow and income increases consumption-based carbon emissions by 0.0253% in the long run. This shows that if the Sub-Saharan African countries want to decrease emissions, they should pay significant attention to factors that enhance their economic growth in the long run.

The outcomes for ECM (−1) are shown in Table 6, which shows that rate of change approaching equilibrium is −0.3188 for CS-ARDL. In the case of ECM (−1), the findings indicate that for every year, roughly 31.88% of the imbalance is rectified. Moreover, the variables for the long-run relationships are greater than those for the short-run relationships, due to the fact that the nations of Sub-Saharan Africa are beginning to emerge, and their industrial growth is still in development, which has a positive impact on carbon dioxide pollution (Khan et al 2020a, b, c). However, the short-run analysis shows that clean energy has a negative significant connection with consumption-based carbon emissions, while income has a positive significant connection with consumption-based carbon emissions. Furthermore, the outcomes of AMG, FMOLS, and DOLS all corroborated the CS-ARDL outcomes (Fig. 1).

DH Granger causality outcomes

According to the results of the Dumitrescu and Hurlin (2012) Granger causality test shown in Table 7, it can be seen that there is a feedback connection between the dependent variable CCO$_2$ and other coefficients such as income, clean energy, and urbanization, while natural resources rent has a uni-directional connection with the dependent variable CCO$_2$. However, both trade flow and the interaction between trade flow and income have no connection with the dependent variable CCO$_2$ (Table 8) .

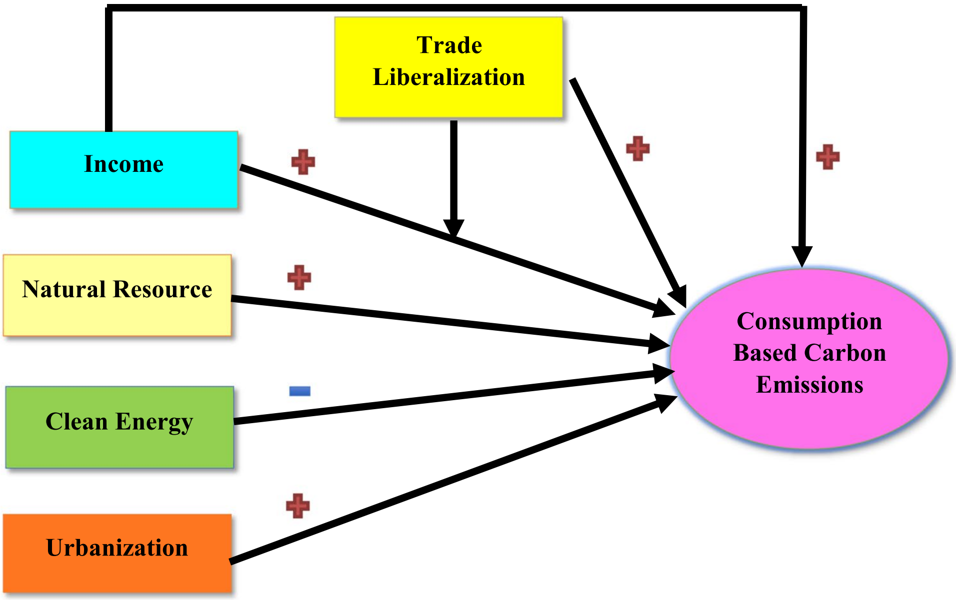

Fig. 1 Graphical outcomes of FMOLS, DOLS, AMG, and CS-ARDL

Conclusion and policy direction

Conclusion

Increasing economic activities in emerging countries such as Sub-Saharan African nations raises the demand for energy, which is mostly derived from traditional sources. More traditional energy usage will have a significantly detrimental influence on the environment. As a result, policymakers' focus has recently shifted to promoting renewable energy generation and consumption across economic activities in order to secure a low-carbon economy. Given this knowledge, we aimed to assess the effect of trade liberalization as well as clean energy on consumption-based carbon emissions (CCO_2) for the case of the Sub-Saharan African nations. Furthermore, we incorporated other determinants of CCO_2 emissions such as urbanization and natural resource into the model. In addition, the joint effect of income and trade liberalization on CCO_2 is examined. To the best of the investigator's knowledge, this is the first research to assess the joint effect of trade liberation and income on CCO_2 emissions. Therefore, the gap in the existing literature is filled. The research utilized a dataset stretching between 1990 and 2018 and second-generation approaches such as CIPS and CADF, Westerlund cointegration, slope heterogeneity, CD, CS-ARDL, and Dumitrescu and Hurlin (2012) causality. The outcomes of the CS and heterogeneity tests supported the utilization of 2nd-generation techniques. Furthermore, the Westerlund cointegration outcomes disclosed evidence of a long-run interconnectedness between CCO_2 and the regressors. The outcomes of the CS-ARDL revealed that trade liberalization, income, economic globalization, and urbanization trigger CCO_2 emissions, while clean energy mitigates CCO_2 emissions. In addition, the joint effect of income and trade liberalization contributes to an increase in CCO_2 emissions. Furthermore, the outcomes of the panel causality unveiled that income, trade liberalization, economic globalization, and natural resource can all predict CCO_2 emissions significantly. Therefore, any policy recommendations directed towards all the regressors will impact CCO_2 emissions.

Policy directions

According to the findings of this study, in order to minimize CCO_2 emissions in Sub-Saharan Africa, policymakers should implement a variety of reforms to restrict the use of nonrenewable energy and raise the percentage of renewable energy. Furthermore, public–private partnerships in renewable energy should be fostered in order to develop greener processes of manufacturing. Furthermore, a circular economy for all sectors should be built, with the recycling of waste and industrial products being actively supported. Because of the economic benefits, policymakers in Sub-Saharan Africa should recognize the need to develop innovation, environmental legislation, and green technology in order to effectively reduce ecological deterioration. Growing emissions from expansion and industrialization will represent a threat to ecological protection if this situation continues. As a result, establishing a pervasive forum to boost R&D collaboration, improve publication as well as readiness, augment cooperative measures for green novelty, promote individual interactions, permit the transfer of clean technology, and generate a fully working linkage and enforce research and enterprise-focused projects is urgently needed.

Redesigning applicable regulations on the imports of goods produced by low-energy-intensive sectors and requiring low energy usage is a significant policy instrument that must be adopted and vigorously implemented. Firstly, this will minimize the volume of embodied carbon imported to Sub-Saharan African countries. Second, decreased energy usage means that less non-renewables will be imported for energy production. Emerging economies, such as those in Sub-Saharan Africa, must keep a close eye on carbon emissions to identify if and when they decouple from economic expansion. If they do not, they will have to build models to solve the problem; otherwise, as the pressure of climate change grows, decarbonization will be at the price of their economic expansion.

Author contribution Bright Gyamfi collect data and interpret. Tomiwa Sunday Adebayo wrote the methodology and policy. Uzoma Ogbolime wrote the literature review.

Data availability Data is readily available at the request from the corresponding author.

Declarations

Ethics approval This research complies with internationally accepted standards for research practice and reporting.

Consent to participate Not Applicable.

Consent for publication Not Applicable.

Competing interests The authors declare no competing interests.

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