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RESEARCH ARTICLE

The effects of trade openness on CO_2 emissions in Sub-Saharan Africa: fresh evidence from new measure

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Abstract
This study assesses the effects of trade openness on carbon dioxide (CO_2) emissions in Sub-Saharan Africa (SSA). In contrast to previous studies, and in order to make a significant contribution to the empirical literature on the subject, we capture trade openness through a new and innovative approach that takes into account not only the share of a country's trade in its gross domestic product but also the size of its trade in world trade. In addition, this study also stands out for its consideration of trade openness in different sectors of the economy (primary, secondary and tertiary). For the econometric strategies, the study used data from 38 SSA countries between 2002 and 2022 and estimated the effects by the Generalized Method of Moments (GMM) system and the double ordinary least squares method. The main results show that in SSA: trade openness contributes to rising CO_2 emissions. In addition, trade in the primary (agriculture), secondary (industry) and tertiary (services) sectors contributes to the increase in CO_2 emissions. The models used are controlled by several variables. The results show that the renewable energy consumption is a key driver of environmental quality, which seems to reduce CO_2 emissions. On the other hand, human capital, population growth and the quality of institutions increase CO_2 emissions. Furthermore, the interaction between openness and institutional quality has a negative impact on CO_2 emissions. Therefore, in order to reduce CO_2 emissions, SSA needs to put the environment on the agenda of future trade negotiations; to implement policies and strategies that guarantee growth without abandoning the environment.

Keywords: Trade openness, CO_2 emissions, Sub-Saharan Africa.

Introduction

In the context of trade protectionism impacting economic and environmental sustainability, a more comprehensive understanding of the impact of trade on carbon emissions is critical to economic and environmental sustainability (Wang et *al.* 2024). The global economy is facing environmental problems that, for the most part, are the results of CO_2 air pollution. In addition to the serious environmental challenges posed by global warming and climate change, concerns about emissions are central to policymaking in many countries (Junaid et *al.* 2023). Among the causes of environmental damage, CO_2 emissions are known to represent the main contributor to recent climate change (Mengal et *al.* 2019; Cai et *al.* 2018). The global challenge of climate change has prompted countries worldwide to shift towards renewable energy sources to reduce CO_2 emissions and mitigate the impacts of climate change (Mohsin, 2024; Kwakwa, 2023). Among the greenhouse gases responsible for climate change, carbon emissions have the greatest impact. Indeed, these emissions account for 80% of total emissions, and reducing them has become an effective way of tackling climate change (Huang et *al*. 2022). Global warming and greenhouse gas emissions pose a serious threat to environmental sustainability in every country in the world. A sustainable environment is a prerequisite for long-term socioeconomic growth and human survival (Haseeb et *al*. 2023). Moreover, global CO_2 emissions have risen remarkably over the years, from 3,112,685,279 metric tons per capita in 1960 to 3,874,290,347 metric tons per capita in 1980 and over 13 billion metric tons per capita in 2018, according to World Bank data (WDI, 2023). International entities have highlighted the issue of climate change and global efforts toward becoming carbon neutral by 2050 (Emma, 2024).

Global warming is one of the most severe environmental problems that human beings are currently facing. The rising level of CO_2, the primary contributor to the greenhouse effect, appears to exacerbate the situation (Goswami, 2023).The substantial increase in CO_2 emissions is alarming, as they have had a negative impact on economic wealth, human health, food security and, to a greater extent, the environment (Duodu & Mpuure, 2023). The quest for rapid economic development by modern nations has led to an unprecedented increase in carbon emissions (Chhabra et *al*. 2023). Global warming due to CO_2 emissions is leading to a reduction in food production and biodiversity, as well as rising sea levels and mortality rates (Liu et *al.* 2022a). According to Intergovernmental panel on climate change (IPCC, 2021), the most important GHG is CO_2, accounting for around 72% of emitted gases. CO_2 emissions contribute to 76% of global GHG emissions (Coskuner et *al.* 2020; Zakari & Tawiah, 2019). The increase in world carbon emissions is always in line with national economic growth programs, which create negative environmental externalities (Hariyani et *al.* 2024). Although SSA is not one of the main CO_2 emitters, the area is exposed to the major harmful effects of CO_2 emissions, which hampers its economic growth and development (Duodu and Mpuure, 2023). For example, CO_2 emissions in SSA rose from 784540.02 kilotonnes (kt) in 2016 to 823770.02 kt in 2019, representing a growth rate of 2.75% in 2019 versus 1.57% in 2016 according to World Bank data (WDI, 2023). Furthermore, although SSA accounts for less than 3% of global carbon emissions, these emissions are increasing over these decades, given ongoing economic and institutional reforms aimed at improving economic growth, strengthening industrialization and diversification, improving transport systems and responding to energy crises (Avom et *al.* 2020). With specific regard to Africa, it has been documented that decision-makers in SSA are very concerned because the consequences of global warming are the most damaging in the sub-region (Efobi et *al.* 2019). SSA's economic and social status is still precarious and open to internal and external shocks (Andriamahery et *al.* 2022). The developing economies of Africa, and more specifically the countries of SSA, have deployed various practices to ensure the emancipation of their level of sustainable development. Some of these include the promotion of economic growth, industrialization, real agricultural development, financial development, renewable energy consumption and human capital sustainability (Ganda, 2021). 600,000 people die every year in the African region from causes related to emissions from wood and charcoal combustion (Chirambo, 2018). The situation is more severe for SSA due to poverty, low technological know-how and most importantly, more than half of the population depends on climate-driven enterprises such as small-scale farming, peasant farming, agriculture and hawking (Ngwenya et *al.* 2018). Although SSA is the least integrated and pollutes the environment the least, it is the most vulnerable to future climate change (Acheampong et *al.* 2019). The main contributors are South Africa, Angola and Nigeria, with 853107.128 kt, 34693.487 kt and 120369.275 kt emitted in 2019 respectively. Guinea-Bissau, Comoros and Sao Tome and Principe represent the lowest levels, with 293.36 kt, 201.685 kt and 121.011kt of CO_2 emitted in 2019 (WDI, 2023). Furthermore, economic openness through the trade dimension and inward foreign direct investment (FDI) influences environmental damage (Sun et *al.* 2019). The link between trade openness and CO_2 emissions is a key research focus in times of pressing global sustainability needs and ongoing climate change discussions (Barkat et *al.* 2024). With this in mind, it has been proven that around a quarter of CO_2 emissions are associated with trade flows (Brenton & Chemutai, 2021). Moreover, economic openness has increased in recent decades, and this is revealed by measures of trade and financial openness (Lemaallem & Outtaj, 2023). Expansion in world trade gives rise to more production and therefore more creation of industrial structures and units. This broad expansion of production requires energy, considered to be the potential source of CO_2 emissions. Researchers assert that trade openness in a country means greater use of natural resources, which ultimately has a negative impact on the environment (Zamil et *al.* 2019). Compared to other regions, statistics on SSA show that the region contributed 36.81% of global trade in 2016 and 30.04% of air pollution in 2014 (World Bank, 2020). The share of trade in SSA's gross domestic product (GDP) rose from 45.98% in 2016 to 50.03% in 2020 (World Bank, 2022). SSA countries have been relatively open to foreign trade since the 1980s. On average, they have recorded a relatively higher rate of growth in CO_2 emissions than other regions, and are the least resistant to the adverse effects of global warming. Today, SSA's objective is to eradicate energy poverty and income inequality in order to achieve the Sustainable Development Goals. With this in mind, several studies have therefore focused on the problems of income inequality, energy and poverty (e.g. Santiago et *al.* 2020; Potrafke, 2015). In contrast, the environmental problems associated with rising CO_2 emissions in the region have been relatively ignored. However, there are growing concerns about the consequences of economic openness on non-economic variables. Furthermore, the relationship between trade openness and CO_2 emissions in SSA has not been deeply investigated by previous researchers.

Most studies focus on developed countries because of their level of industrialization. A few studies carried out in SSA focus on countries such as South Africa (Udeagha & Ngepah, 2019; Mapapu & Phiri, 2018), Nigeria (Zakari & Tawiah, 2019) and Ghana (Kwakwa et *al.* 2020; Solarin et *al.* 2017). Since the early 1990s, a large and growing literature has studied the role of trade openness in CO_2 emissions. However, empirical contributions have remained contradictory and inconclusive. It appears from the literature that trade openness is one of the methods or strategies that can be used to achieve economic growth (Gnangnon, 2020). However, the real question is how much it will cost. While SSA needs economic growth, we must not lose sight of the need for long-term growth. Therefore, growth that takes into account the quality of the environment must be a top priority. This highlights the link between trade openness and the environment in SSA (Andriamahery et *al.* 2022). In an era defined by the urgent need for global environmental sustainability and amid ongoing discussions surrounding climate change mitigation, the relationship between trade openness and CO_2 emissions has emerged as a paramount field of investigation (Barkat et *al.* 2024). The consequences of CO_2 emissions in SSA countries cannot be ignore given it adverse effect on human health and global warming (Ewane & Ewane, 2023).

This article is structured around five points: an introduction, which sets the context for the subject and analyzes the stylized facts of CO_2 emissions in SSA; a literature review, which clearly shows the lack of consensus in theoretical and empirical studies and also develops a new indicator of trade openness; a methodology, which presents the model specification, the estimation method and defines the model variables; results and discussions, which clearly present the estimation results and their interpretations; and finally, the conclusion and policy recommendations.

Literature Review

The ever-debated relationship between trade and environment has allured the attention of many scholars over a long period (Chhabra et *al.* 2023). The importance of enhancing environmental quality to promote economic development by improving societal well-being and sustainable development on quality of environment haveattracted significant attention from researchers in recent years (Mekuannet, 2024). Existing theoretical literature has identified three channels in international trade through which CO_2 emissions can be affected by trade openness: the scale effect, the composition effect and the technical effect (Antweiler et *al.* 2001). Grossman & Krueger (1993) consider these mechanisms to be the economic determinants of emissions from productive activity. They are economic growth (scale effect), industrial composition (composition effect) and the severity of environmental regulation (technical effect). While the theoretical literature has documented various channels through which openness to international trade can affect environmental quality, its empirical verification remains an open and controversial question for researchers and policy-makers alike. The impact of trade openness on environment is of increasing concern to environmental practitioners, industrialists, and researchers (Dou et *al.* 2023).

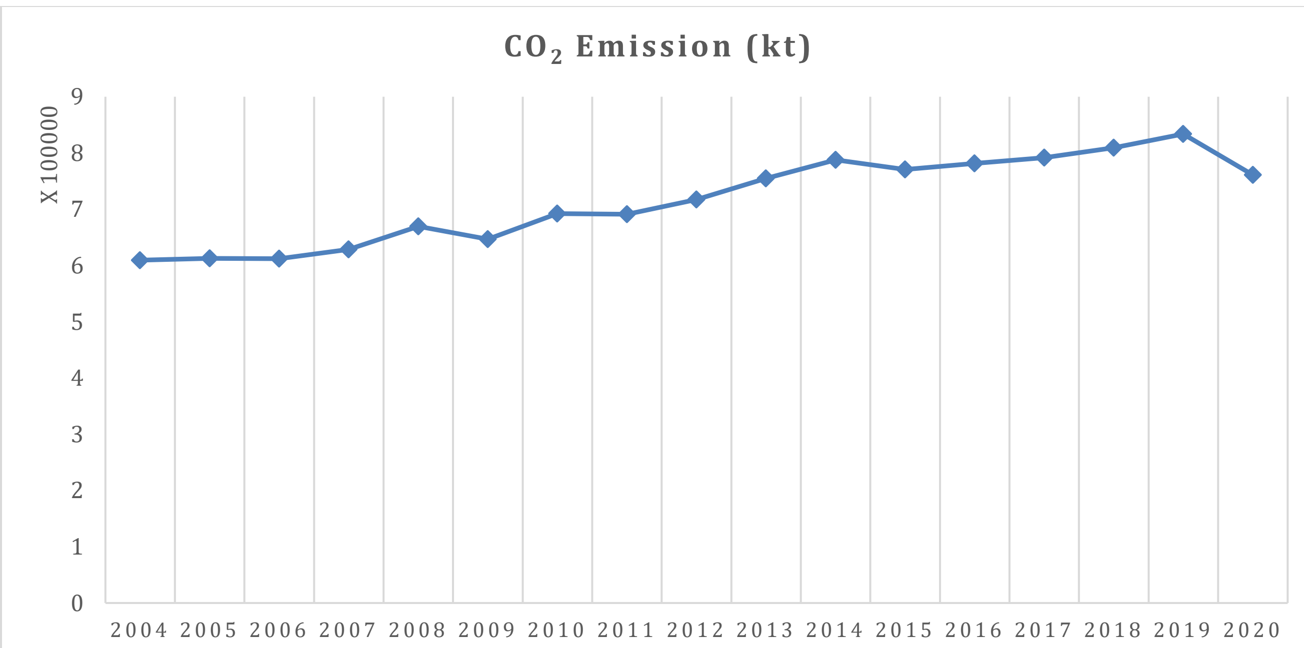

Figure 1. Trends in CO_2 emissions (in kilotonnes) in SSA (2004-2020)

Figure 1 shows the evolution of CO_2 released into the atmosphere by SSA. According to World Bank data (WDI, 2023), CO_2 has followed an upward trend, rising from 497660 kt in 2000 to 695130 kt in 2010, 789380 kt in 2014 and 823770.016 kt in 2019. While some recent studies have shown that trade decreases CO_2 emissions from the development of new energy-saving technologies (e.g. Duodu & Mpuure, 2023; Ibrahim & Ajide, 2022; Okelele et *al.* 2022; Iheonu et *al.* 2021; Muhammad et *al.* 2020; Aydin and Turan, 2020; Kwakwa et *al.* 2020; Awad, 2019; Hu et *al.* 2018; Sinha & Shahbaz, 2018; Acheampong, 2018). Others have found that such activities are harmful to the environment (e.g. Andriamahery et *al.* 2022, Chen et *al.* 2021; Duodu et *al.* 2021; Du et *al.* 2020; Hakimi & Hamdi, 2020; Zamil et *al.* 2019; Acheampong et *al.* 2019; Balsalobre-Lorente et *al.* 2018; Raza & Shah, 2018). In contrast to all these empirical investigations, some studies have provided evidence suggesting that openness has no statistically significant impact on CO_2 emissions (e.g. Salahuddine et *al.* 2019; Inglesi-Lotz & Dogan, 2018; Mapapu & Phiri, 2018; Inglesi-Lotz, 2018). Consequently, regarding the effect of trade openness on CO_2 emissions, the evidence is largely contradictory, and no consensus has been found or reached in the empirical literature. Table 1 below summarizes a number of empirical studies on the effects of trade openness on CO_2 emissions.

Table 1. Summary of empirical studies on the relationship between trade openness and CO_2 emissions

Authors	Periods and Country	Methods used	Results
Bouchoucha (2024)	1990-2019 40 African countries	Simultaneous equations	The results show that trade openness has a positive and significant effect on CO_2 emissions, and therefore CO_2 emissions have a positive association with infant mortality and under-five mortality, while CO_2 emissions have a negative association with life expectancy.
Ghaderi et *al.* (2023)	1995-2018 Middle East and North Africa (MENA)	Granger's test of non-causality, the estimator of the mean group of correlated effects.	Energy consumption and trade openness are the main contributors to CO_2 emissions. The results also showed that although first-generation estimators confirmed the Environmental Kuznets curve (EKC) hypothesis, there is no inverted U-shaped association between economic progress and CO_2 emissions.
Goswami et *al.* (2023)	1981-2021 India	ARDL model and the random forest model	The ARDL model revealed that variables were co-integrated. In the short term, economic growth and trade openness are correlated with CO_2 emissions, while energy consumption and urbanization were positively correlated. In the long term, energy consumption, urbanization and commercial opening are positively correlated with CO_2 emissions, while economic growth and CO_2 emissions are positively correlated.
Pham & Nguyen (2024)	2003-2017 64 developing countries	Bayesian approach to the average	There is no evidence of a statistically significant effect of trade opening on environmental pollution in developing countries. However, the results do not support the pollution paradise hypothesis. In addition to trade openness, the results indicate that financial openness, renewable energy consumption and capital abundance are key drivers of environmental quality, which appear to reduce CO_2 emissions.
Barkat et *al.* (2024)	20 Organisation for Economic Co-operation and Development (OECD) countries over a period of 150 years	Robust cointegration techniques	The direct effect showed a positive correlation between trade opening and CO_2 emissions, while the indirect effect, mediated by income growth, shows a negative influence. These divergent effects support the environmental Kuznets curve hypothesis.
Duodu & Mpuure (2023)	1990-2020 ASS	GMM and the Dumitrescu and Hurlin (D-H) causality test	The overall effect of trade reduces environmental pollution by around 0.10% and 0.79% in both the short and long term, respectively. Again, we observe that exports and imports minimize environmental pollution, we observe that exports and imports minimize environmental pollution by around 0.07% and 0.45% (0.08% and 0.58%) in the short term (long term), respectively. With regard to the D-

			H results, we found a bidirectional causality between total trade and environmental pollution.
Chhabra et *al.* (2023)	1991-2019. BRICS	modern method of dynamic common correlative effects	Confirming the pollution paradise hypothesis, the results reveal that "trade opening" is indeed a cause of environmental damage in BRICS countries.
Omri E. & Saadaoui (2023).	1980-2020 France	NARDL (Non-linear Autoregressive Distributed Lag	Fossil fuels and open trade are increasing emissions. The analysis confirms the presence of an inverted U-curve linking economic growth to carbon emissions.
Ewane & Ewane (2023)	1975-2020 SSA countries	a quadratic modelling approach	It shows evidence that trade openness and foreign direct investment contribute to reducing CO_2 emissions in the short term, but increase in the long term. The study recommends that SSA countries adopt strong environmental policies to achieve sustainable economic growth without harming the environment.
Dou et *al.* (2023)	1990-2021. 76 countries	Non-linear dynamic model	Trade openness has a significant impact on carbon productivity, with a U-shaped relationship between the two variables. In other words, carbon productivity first decreases and then increases from a certain threshold of trade opening. The impact of trade opening on carbon productivity varies from country to country.
Pata et *al.* (2023)	1995-2018 Association of South-East Asian Nations (ASEAN) countries	The ARDL panel estimator and the Dumitrescu-Hurlin panel causality test	Real income and trade openness reduce environmental damage. The EKC hypothesis is valid because the elasticity of income in the long term is lower than in the short term.Renewable energy reduces carbon emissions only in the short term and has no effect on environmental quality in the long term. There is no causal relationship between renewable energy and environmental damage.
Udeagha & Breitenbach (2023)	1960-2020 Southern African Development Community (SADC)	Non-linear, autoregressive distributed delay (NARDL)	The results show mixed evidence of an asymmetric behaviour between trade opening and CO_2 emissions. Long-term asymmetry is found for Botswana, Madagascar, Mozambique and Tanzania, while for the Comoros, Namibia and South Africa there is evidence of both short- and long-term asymmetry. The other cases (Angola, Democratic Republic of the Congo (DRC), Lesotho, Malawi, Mauritius, Seychelles, Zambia and Zimbabwe) show ample evidence of symmetrical behaviour and long-term linear relationships between trade opening and CO_2 emissions.
Junaid et *al.* (2023)	1990-2019 75 BIS countries	Spatial panel data models and methods	First, the estimated results confirm the existence of spatial self-correlations in CO_2 emissions between BIS countries. Second, the trade opening, natural gas consumption and spatial

			effects of these variables positively affect CO_2 emissions.
Awad (2019)	(1990-2017) 46 African countries	DOLS, and a non-parametric technique (FMOLS).	The results suggest that intra-African trade has improved environmental quality on the continent. In addition, the results confirmed the presence of the Kuznets Environmental Curve
Qamruzzaman M. (2021)	(1971-2019) Low-income countries, lower-middle-income countries, upper-middle-income countries and a global sample	Nonlinear ARDL, non-Granger causality test	The results show that positive relationships run from environmental quality, institutional quality and FDI to trade openness, particularly in the long term. Furthermore, asymmetric estimation establishes asymmetry shocks in environmental quality, institutional quality and FDI that are positively related to trade openness, particularly in the long term. Furthermore, the results of the Wald test confirm the presence of asymmetry in both the long and short term..
Andriamahery et *al.* (2022)	(1990-2017) SSA	GMM	The results show that trade significantly increases N_2O, ACH4 and CO_2 emissions for the overall sample of Sub-Saharan Africa and its income groups (upper-middle-income countries, lower-middle-income countries and low-income countries).
Zamil et *al.* (2019)	(1972-2014) Oman	Unit Root Tests, ARDL	GDP, population and trade openness seem to have a positive impact on CO_2 emissions.
Hu et *al*. (2018)	1996-2012 25 developing countries	DOLS, and a non-parametric technique (FMOLS).	trade improves the environment by reducing carbon emissions.
Acheampong (2018)	1990-2014 116 countries of the world	VECM, GMM	open trade improves environmental quality by reducing carbon emissions worldwide,,
Kwakwa et *al*. (2020)	1971-2013 Ghana	theoretical framework composed of the STIRPAT, ARDL model	International trade leads to a reduction in CO_2 emissions in Ghana.
Sinha & Shahbaz (2018)	1971-2015 India	unit root test and (ARDL)	trade openness is negatively correlated with carbon dioxide emissions in India
Hakimi & Hamdi (2019)	2006-2015 143 countries	GMM	Trade is detrimental to the quality of the environment, and the role of institutions is crucial to preserving it.
Acheampong et *al*. (2019)	1980-2015 46 SSA countries	fixed and random effects estimation techniques	Open trade worsens the environment
Raza et Shah (2018)	1972-2014 Pakistan	Ordinary least squares	trade openness deteriorates environmental quality.
Nguyen et *al*. (2020)	1996-2014 33 emerging economies	theoretical framework composed of the STIRPAT, ARDL model	Openness has a positive impact on CO_2 emissions in the short term and a negative impact on CO_2 emissions in the long term.

Udeagha & Ngepah (2019)	1960-2016 South Africa	ARDL	while trade liberalization has a significantly beneficial impact on CO_2 emissions in the short term, it has a detrimental effect in the long term.
Sun et *al.* (2019)	Countries of the South Asian Association for Regional Cooperation (SAARC).	ARDL	Trade, FDI and economic growth have a positive long-term correlation with environmental damage in SAARC countries; whereas FDI and trade flows have a negative relationship with CO_2 emissions in the short term.
Inglesi-Lotz (2018)	1990-2014 BRICS	CO2 Emission Technical breakdown	Commercial openness has no significant impact on environmental conditions.
Mapapu &Phiri (2018)	1970-2014 South Africa	Quantile regression	very low CO_2 emissions are most beneficial for economic growth, and that trade openness has no significant impact on carbon emissions.
Inglesi-Lotz & Dogan (2018)	1980-2011 10 SSA countries	Technical assessment panel robust to cross-sectional dependence	Trade openness has no significant effect on carbon dioxide emissions.
Salahuddin et *al*. (2019)	1984-2016 44 SSA countries	Second-generation panel regression techniques	The effect of globalization (FDI and trade openness) on CO_2 emissions is statistically insignificant.
Kim et *al.* (2019)	Northern countries, southern countries	Instrumental variable panel quantile approach	Northern trade contributes to rising CO_2 emissions, while southern trade reduces CO_2 emissions
Mutascu (2018)	1995-2011 G7 countries	Granger causality	Significant heterogeneity between G7 countries in terms of international trade and environmental issues. Trade openness is a good indicator of CO_2 emissions generated by the production sector.
Sun et *al.* (2019)	1991-2014 49 countries	Current panel cointegration approaches	The study reveals that trade openness has both positive and negative effects on environmental pollution, but the effect varied across these different groups of nations.
Aydin & Turan (2020)	1996-2016 BRICS	Cross-dependency testing, unit root testing, conitegration testing	Open trade reduces pollution in South Africa and India.

Source: Author's compilation.

Note: GMM=Generalized Method of Moments; CO_2=carbon dioxide, SO_2=sulfur dioxide,, SSA=Sub-Saharan Africa; FMOLS= Fully Modified Ordinary Least Square, DOLS= Dynamic Ordinary Least Square, ARDL= autoregressive distributed lag model, VECM= vector error correction model, STIRPAT= Stochastic impacts by regression on population, influx and technology, BRICS= Brazil, Russia, India, China and South Africa, CEE= Central and Eastern European Countries, OECD=Organization for Economic Cooperation and Development.

Table 1 shows that there is a consensus in empirical studies Therefore, it is clear that the theoretical arguments and empirical results of the effect of trade liberalization and FDI on CO_2 emissions are unclear and contradictory (Hakimi & Hamdi, 2016). There is no doubt that the contradictory results of the effects of trade on environmental pollution can, to some extent, be attributed to methodological weaknesses and, it is also possible that the environmental effect of trade depends on the nature of trade (Duodu & Mpuure, 2023). The heterogeneity of data and empirical methods used in these studies can partly explain the diversity of results and contradictory positions in the literature. The diversity may depend on a myriad of factors of different countries selected in the sample, the econometric techniques employed, environmental indicators and a set of control variables used. Other likely reasons for these conflicts include how trade openness is described and measured.

However, despite its popularity, the traditional measure of trade openness and its variants should be used with caution for a number of reasons, most of which are related to GDP normalization (Gräbner et *al.* 2021). Another possible explanation for the contradictions is that the authors evaluate the hypothesis by ignoring the importance of structural effects that stimulate economic growth (Nkengfack et *al.* 2019).

The present study is innovative in that it introduces variables that are recommended by researchers in the current literature on growth and the environment. Indeed, to describe the proxy variable for trade openness, this study uses two indicators: the composite trade intensity of Squalli & Wilson (2011) and the openness rate (a traditional indicator of openness). In order to see which sector contributes the most to CO_2 emissions, this study takes into account the openness in different sectors of the economy (primary, secondary and tertiary).

Development of the new indicator of trade openness

Following the various criticisms addressed to the degree of openness as a measure of the level of trade openness of a country, we develop, in accordance with Squalli & Wilson (2011), a new indicator taking into account both dimensions of openness. However, despite its popularity, Trade/GDP and its variants should be used with caution for a number of reasons, most of which are related to the normalization by GDP. In order to take into account the arbitrage bias that exists in the use of unidimensional measures of openness, we will propose an alternative method of calculating these indicators. This method takes into account both unidimensional measurement criteria (TI and WTS).

$$WTS_i = \frac{(X+M)_i}{\sum_{j=1}^{n}(X+M)_j}$$

, in this formula we can rewrite the volume of world trade as follows:

$$\sum_{j=1}^{n}\left(X+M\right)_j = \left(X+M\right)_i + \sum_{J=1}^{n-1}\left(X+M\right)_J \tag{1}$$

$$= X_i + M_i + \sum_{j=1}^{n-1} X_i + \sum_{j=1}^{n-1} M_i$$

With $\sum_{j=1}^{n-1} X_i$ and $\sum_{j=1}^{n-1} M_i$ respectively the volume of exports and imports from the rest of the world. If the exports of country i (X_i) are almost equal to what the rest of the world exports and what country i imports (M_i) are almost equal to the exports of the rest of the world, in other words if the quantity of products exported by country i to the rest of the world is the same, and that imported by the latter is also equal to the quantity imported by the rest of the world; then we will have:

$$\sum_{j=1}^{n}\left(X+M\right)_j = 2\left(X+M\right)_i \Leftrightarrow \frac{\left(X+M\right)_i}{\sum_{j=1}^{n}\left(X+M\right)_j} = \frac{1}{2} \quad (2)$$

WTS cannot therefore exceed 0.5 since no country can export and import more than the rest of the world. Alternatively we will have:

$$\sum_{i=1}^{n}\left[\frac{\left(X+M\right)_i}{\sum_{j=1}^{n}\left(X+M\right)_J}\right] = 1 \quad (3)$$

$$\bar{x} = \frac{\sum_{i=1}^{n}\left[\frac{\left(X+M\right)_i}{\sum_{j=1}^{n}\left(X+M\right)_J}\right]}{n} = \frac{1}{n} \quad (4)$$

The new measure of trade openness takes into account the two previous criteria *WTSi* and *TIi*, that is, between the trade intensity of the country in relation to the performance of its local economy on the one hand, and on the other hand, it takes into account the relative trade intensity of the latter in relation to the volume of world trade. And it can be presented as a "composite trade intensity measure" *CTI* in the following form:

$$CTI_i = \left(1 + D_y\right) TI_i \quad (5)$$

With D*y* representing the ratio of the measured distance to the deviation of from the mean and is presented by the following form:

$$D_y = \frac{WTS_i}{\bar{X}} - 1 \quad (6)$$

$D_y \geq 0$, when $WTS_i \geq 0$ and $D_y \leq 0$ if $WTS_i \leq 0$

According to these last two formulas and replacing equations (1) and (4) by their expressions, we will have: $CTI_i = \frac{1}{\bar{X}}(WTS_i \times TI_i) = \text{n}(WTS_i \times TI_i)$, by replacing *WTS* and *TI* by their expressions, we will finally have the expression of the new indicator of trade openness:

$$CTI_i = \frac{n(X+M)_i^2}{PIB_i \sum_{j=1}^{n}(X+M)_j} \quad (7)$$

Where *CTI* stands for composite trade intensity which is the new indicator for measuring trade openness. When comparing TI-based trade openness measures, a striking anomaly arises. Indeed, as shown in Table 2, according to *TI*, China, Russia, Malaysia, Japan and the United States are among the most closed economies in the world. On the contrary, Equatorial Guinea and Congo belong to the most open countries in the world. Consequently, according to TI, the world's largest trading powers are relatively closed economies, because their share of trade (*WTS*) in overall economic activity is very low by global standards. But is it right to classify countries like the United States, the leading trading power, Japan and Russia as closed economies? The obvious explanation is that TI and related indicators are one-dimensional measures of trade openness and in this way, they penalize large economies by classifying them as closed. Table 2 ranks countries according to squalli & wilson (2011) indicators of trade openness.

Table 2. Ranking of countries according to trade openness indicators

Countries	X+M/GDP	Rank	WTS	Rank	CTS	Rank
Cameroon	57,44	100	0,083	84	645,90	89
Congo	132,5	18	0,043	100	767,59	86
Gabon	71,79	76	0,029	109	282,08	105
Equatorial Quinea	153,05	10	0,03	107	630,81	93
Chad	48,6	112	0,015	117	99,72	122
United States	26,2	133	10,810	1	38517,96	9
Japon	20,1	136	2,781	10	7603,43	35
Russia	70,68	77	8,210	4	41574,34	7
Belgium	169,33	7	1,826	19	42056,33	6
China	48,36	113	9,841	2	64724,01	4
Hong Kong	295,19	2	2,354	14	94491,06	1
Malaysia	230,33	4	2,124	17	66527,34	3

Source : Squalli & Wilson (2011)

Methodology

To examine the effects of trade openness on CO_2 emissions in SSA, various econometric techniques are used for a panel of 38 countries (Angola, Democratic Republic of Congo, Equatorial Quinea, Ivory Coast, Togo, Eswatini, Mozambique, Botswana, Ghana, Namibia, Uganda, Gabon, Rwanda, Burkina Faso, Guinea, Senegal, Burundi, Guinea-Bissau, Seychelles, Cape Verde, Kenya, Sierra Leone, Cameroon, Madagascar, South Africa, Benin, Nigeria, Niger, Zimbabwe, Mauritius, Lesotho, Malawi, Comoros, Mali, Sudan, Republic of Congo, Tanzania, Mauritius) over the period 2005-2022. The choice of the study period is dictated by the constraint of availability of relevant data on CO_2. All data come from the World Development Indicator and World Governance Indicator of the World Bank (WDI and WGI, 2023).

Model Specification

In this study, we draw inspiration from the above econometric models for the specification of our analysis model. Indeed, following Acheampong et *al.* (2019) and Hakimi & Hamdi (2020), we have the following specification:

$$CO2_{i,t} = \alpha_0 + (1+\beta_1)CO2_{i,t-1} + \beta_2 OUV_{i,t} + \beta_3 PIB/h_{i,t} + \beta_4 PIB^2/h_{i,t} + \beta_5 CapPh_{i,t} + \beta_6 Caphu_{i,t}$$
$$+\beta_7 Df_{i,t} + \beta_8 ER_{i,t} + \beta_9 Pop_{i,t} + \beta_{10} Gov_{i,t} + \Sigma_{i,t} \quad (8)$$

Let's ask $\Sigma_{i,t} = \eta_i + \lambda_t + \upsilon_{i,t}$, with unobservable components such as a country specific component (η_i), a specific time component (λ_t) and the residual term ($\upsilon_{i,t}$). *i* and *t* represent countries and periods respectively. In the form of a dynamic panel model, equation (8) is rewritten as follows:

$$CO2_{i,t} - CO2_{i,t-1} = \alpha_0 + \beta_1 CO2_{i,t-1} + \beta_2 OUV_{i,t} + \beta_3 EE_{i,t} + \beta_4 ET_{i,t} + \beta_5 CapPh_{i,t} + \beta_6 Caphu_{i,t}$$
$$+\beta_7 Df_{i,t} + \beta_8 ER_{i,t} + \beta_9 Pop_{i,t} + \beta_{10} Gov_{i,t} + \Sigma_{i,t} \quad (9)$$

In this model, $CO2_{it}$ represents CO_2 emissions; $OUV_{i,t}$ trade openness; $ET_{i,t}$ technical effect; $CapPh_{i,t}$ physical capital investment; $EE_{i,t}$ scale effect; $POP_{i,t}$ population; $Gov_{i,t}$ institutional governance; $ER_{i,t}$ renewable energy and $Dfi_{i,t}$ financial development, and $CapHu_{i,t}$ human capital.
We can simplify (13) as follows:

$$CO2_{i,t} - CO2_{i,t-1} = \beta_1 CO2_{i,t-1} + \beta_2 OUV_{i,t} + \vec{\beta}_3^{'} CV_{i,t} + \eta_i + \lambda_t + \nu_{i,t} \qquad (10)$$

Where : $CO_{2i,t}$ and $CO_{2i,t-1}$ represent respectively the logarithm of CO_2 emissions in metric tons per capita and the logarithm of the same variable delayed by one period; CV_{it} is the vector of explanatory variables; OUV_{it} is the variable representing trade openness; η_i and λ_t respectively denote the unobserved individual and temporal specific effects; V_{it} is the error term; *i* and *t* represent countries and periods respectively; β_1 and β_2 are parameters to be estimated; $\vec{\beta}_3^{'}$ is the transpose of a parameter vector to be estimated. With *i*=1,,,N and *t*=1,,,T. The hypothesis of convergence between the economies studied suggests that the coefficient (β_1) is negative and significant in the model, i.e. $0 \prec 1 + \beta_1 \prec 1$. We can further rewrite model (10) as follows:

$$CO2_{i,t} = \tilde{\beta}_1 CO2_{i,t-1} + \beta_2 OUV_{i,t} + \vec{\beta}_3^{'} CV_{i,t} + \eta_i + \lambda_t + \nu_{i,t} \qquad (11)$$

With $\tilde{\beta}_1 = 1 + \beta_1$

Consistent with Huang et *al*. (2022), Zheng et *al*. (2021), Ehigiamusoe et *al*. (2020), in order to examine how the effect of trade openness on the environment varies when it interacts with complementary policies (CPs), equation (11) can be modified as follows:

$$CO2_{i,t} = \tilde{\beta}_1 CO2_{i,t-1} + \overline{\beta}_2 CV_{i,t} + \beta_3 OUV * PC_{i,t} + \eta_i + \lambda_t + \nu_{i,t} \qquad (12)$$

In our work, institutional governance is the complementary policy. All data used are in logarithms. Indeed, there are important reasons associated with transforming the data into logarithms. The first is the use of direct elasticities and obtaining more consistent and efficient results. Second, the logarithm specification increases the stationarity of the series. And finally, heteroscedasticity is reduced (Awad, 2019; Zakari & Tawiah, 2019).

Estimation method

This study does not use the Ordinary Least Square (OLS) model, the fixed effect model and the random effect model due to the problem of autocorrelation between the lags of the dependent variables and the error terms as well as the possible problem of endogeneity of the dependent variables. However, following the recent literature on the subject (Yameogo et *al*. 2021; Hakimi & Hamdi, 2020), the Arellano & Bover (1995) system GMM is used to solve these problems. This method eliminates the problem of weak instruments in the analysis, thus making the results of the two-stage process more robust and efficient. We will use this method for the estimation of the model (9). The two-step GMM approach is asymptotically efficient and robust to heteroscedasticity. In order to have efficient estimators, the ratio of the number of individuals (N) to the number of instruments (i) (r=N/i) must be greater than 1 and to solve the problem of the nature of the instruments, it is judicious to introduce variables that have nothing in common such as institutional variables or to delay some or all of the explanatory variables and test their validity by a Sargan and Hansen test (Roodman, 2009).

Definition of variables

Here we define the dependent variable of the study and the explanatory variables. Table 3 describes the variables used in this study.

Table 3. Description of variables.

Variables	Expected sign	Description	Authors	Sources
CO_2 **(**Carbon dioxide emissions)		We use CO_2 emissions in metric tons per capita which in most studies describe environmental quality.	Asif (2024); Adebanjo & Akintunde (2024), Andriamahery et *al.* (2022); Kalayci & Hayaloglu (2019),	(WDI, 2023)
OUV (trade openness)	+	The composite trade intensity of Squalli & Wilson (2011), is used to describe the degree of openness of SSA countries.	Udeagha & Ngepah (2019) ; Udeagha & Breitenbach (2023).	(WDI, 2023)
EE (Scale Effect)	+	Captured as in most studies by GDP/capita.	Shahbaz & Sinha (2019); Sabir et *al.* (2020), To et *al.* (2019), Dauda et *al.* (2019)	(WDI, 2023)
ET (Technical effect)	-	Captured as in most studies by the square of GDP/capita	Awad (2019); Acheampong et *al.* (2019) ; Antweiler et *al.* (2001)	(WDI, 2023)
CaPh (Physical Capital)	+ou-	Captured by gross fixed capital formation (%GDP)	Duodu & Mpuure, (2023); Hakimi & Hamdi (2020); Sun et *al.* (2019); Fauzel (2017)	(WDI, 2023)
CapH (Human Capital)	+ ou -	It is approximated by the secondary school enrollment rate	Andriamahery et *al.* (2022); Dauda et *al.* (2020), Ahmed & Wang (2019); Ponce et *al.* (2019).	(WDI, 2023)
Df (Financial development)	+ ou -	The ratio of domestic credit to the private sector (%GDP) is used	Zakari & Tawiah (2019), Haseeb et *al.* (2018), Ali et *al.* (2019)	(WDI, 2023)
ER (Renewable Energy)	-	Renewable energy consumption (as % of total energy consumption) is used to capture renewable energy	Toumi & Toumi, (2019); Nathaniel & Iheonu (2019); Baloch et *al.* (2019); Waheed et *al.* (2018); Dong et *al.* (2018).	(WDI,2023)
Pop (Population)	+ ou -	Population growth (annual %)	Acheampong et *al.* (2019) ; Huang et *al.* (2022)	(WDI,2023)
GOV (Quality of institutions)	-	The synthetic indicator of six (6) dimensions of governance is used	Habib et *al.* (2020); Usman et *al.* (2019);	(WGI,2023)

Source: author

Results and discussions

Before doing so, however, it is necessary to carry out a descriptive analysis of the study variables and of the correlation matrix between the dependent variable and the different explanatory variables of the model.

Descriptive analysis of variables

The descriptive statistics (Table 4) of the main analysis variables are contained in the table below and show the same number of observations (684) for all variables (38*18=684). The average CO_2 emissions of SSA countries is of the order of (2.9143). The trade openness captured by the Squalli and Wilson indicator (2011) has an average of 1.276.

Table 4: Descriptive statistics of the variables

Variable	Obs	Average	Standard deviation	Min	Max	Sdt.dev	Skewness	Kurtosis	J-B
$EmissCO_{2\sim I}$	684	2.91433	0.25122	19.6215	85.8251	0.6215	0.2584	5.2514	51.21*
Ouv~l	684	1.276606	4.215802	-12.55692	14.21594	0.6252	-1.5215	1.2482	23.14*
EE	684	7.8493	0.321581	-2.65693	2.22592	1.2513	2.0516	8.2154	11.11*
ET~t	684	40.74841	0.592519	-1.987359	1.12548	14.0125	2.1470	7.2154	9.215*
CapPh~é	684	52.19036	0.72318	-1.01227	0.21584	0.2147	2.1111	4.9651	8.858*
Ouv(X+M/PIB)	684	1.57136	0.32582	-1.99927	0.32547	0.4474	1.9686	9.2154	13.36*
OuvPrimary~e	684	2.56074	0.33258	-9.63093	2.01251	0.33332	3.3335	10.1014	12.28*
OuvSecon~n	684	2.62589	0.35489	-1.81262	0.32189	1.4857	3.1117	9.2154	12.11*
OuvTertia	684	2.61299	0.11245	-1.2582	1.25148	4.3251	2.9975	7.8541	8.977*
Caph~l	684	41.10621	4.21548	21.21521	41.41441	2.3152	5.2874	8.3699	23.28*
Df~a	684	5.15507	7.25184	15.21589	99.8921	0.2154	7.6254	8.2157	22.87*
ER~e	684	6.67003	0.34852	-1.01258	1.144352	0.87956	1.2221	5.4849	14.88*
Pop~t	684	15.1267	7.215489	2.01586	89.32145	0.2187	2.3731	6.6696	11.21*
GovInst~l	684	1.9205	25.51482	-15.0215	14.21586	0.77812	-0.2014	0.6598	5.897*

Source: author from world bank data. **Note:** *, ** and *** significance at the respective thresholds of 1%, 5% and 10%.

Furthermore, the traditional indicator of trade openness gives an average of 1.571 while it is of the order of 2.56; 2.62; and 2.61 in the tertiary, secondary and primary sectors respectively. The composition effect captured by the ratio between capital and labor is characterized by the smallest average value (-0.1903) and also the smallest maximum value (0.215). The scale effect captured by GDP per capita has an average of 7.849 while the technical effect has an average of around 40.74. Physical capital is characterized by the largest average value (52.19) followed by human capital (41.106), while financial development has on average the largest maximum value (99.892). Population growth has a mean value of 15.126 while it is of the order of 1.92 for institutional governance. It is also observed that renewable energy consumption has a mean of 6.67. The difference between the minimum and maximum values of all the variables is between 0.2147 and 14.012.

Overall, the descriptive statistics show low variations. The results further show that only institutional governance and trade openness are negatively skewed while the others are positively skewed. The Kurtosis values reveal that governance and trade openness are platykurtic while the other variables have a leptokurtic distribution. The Jarque-

Table 5. Correlation matrix between variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$EmissCO_2$~I	1.0000													
Ouv~l	0.0147	1.0000												
EE	0.3744	0.1002	1.0000											
		-												
ET~t	-0.5897	0.0586	0.7265	1.0000										
CapPh~é	0.2147	0.1104	0.8420	0.7220	1.0000									
			-											
Ouv(X+M/GDP)	-0.3360	0.0519	0.6746	0.6275	0.6519	1.0000								
OuvPrimary~e	0.2871	0.0538	0.8141	0.7534	0.9110	0.6311	1.0000							
OuvSecon~n	0.2544	0.0765	0.8858	0.7944	0.9090	0.7472	0.8785	1.0000						
OuvTertia	-0.2581	0.0806	0.8701	0.7857	0.9271	0.8635	0.9097	0.9956	1.0000					
		-	-			-			-					
Caph~l	-0.0651	0.0200	0.1121	0.0079	0.1149	0.1336	0.0103	0.1419	0.1169	1.0000				
		-	-	-	-	-	-	-	-					
Df~a	-0.0122	0.0828	0.0767	0.0887	0.0747	0.1087	0.0924	0.0924	0.1112	0.0009	1.0000			
											-			
ER~e	-0.3281	0.0129	0.1630	0.2536	0.3027	0.3271	0.2298	0.2450	0.3098	0.0976	0.0199	1.0000		
							-			-	-			
Pop~t	0.3697	0.0628	0.1008	0.1932	0.2320	0.0960	0.2251	0.1495	0.1836	0.1130	0.0178	0.2503	1.0000	
										-	-			1.0000
GovInst~l	-0.0213	0.9998	0.0147	0.4472	0.2140	0.0147	0.3251	0.9980	0.1987	0.0580	0.0258	0.9871	1.0000	

Source: Author from world bank data

Bera statistic affirms the normality of our data series, which indicates the adequacy of the data for any empirical analysis.

Correlation matrix analysis

Table 5 provides a description of the correlations between the different analysis variables. The correlation matrix shows the existence of correlations between the different variables used. The correlations between CO_2 emissions and GDP per capita on the one hand, CO_2 emissions and the square of GDP on the other hand, are 0.3744 and -0.5897 respectively. The correlations between CO_2 emissions and physical capital; CO_2 and trade openness (Squalli & Wilson, 2011) are 0.2147 and 0.0147 respectively. Furthermore, the highest correlations appear between trade openness and institutional governance (0.9998); between openness in the secondary sector and governance (0.998); between openness in the secondary sector and openness in the tertiary sector (0.9956).
Indeed, having an observation of more than 200 can result in a correlation coefficient between 0.7 and 0.8 without causing a problem in the estimations. This proves that there is no multi-collinearity between the independent variables. However, the weakest correlations appear between CO_2 emissions and the scale effect (-0.5897), between CO_2 emissions and trade openness captured by the traditional indicator (human capital and the composition effect (-0.9816); -0.3281 between institutional governance and trade openness captured by the traditional indicator (-0.1204); governance and CO_2 emissions (-0.1750); between CO_2 emissions and renewable energy consumption (-0.3281) and finally population growth and openness in the primary sector (-0.2251). However, the correlations between the different variables analyzed are not

Presentation and interpretation of the results

Here, we present and interpret the results obtained by the generalized moments method as well as the interpretations. This part therefore begins with the presentation of the results obtained using the generalized moments method in system. For the sensitivity of the results, we re-estimate the model using the Ordinary Double Least Squares method. In all estimations, the reported coefficients are in logarithms, hence can be interpreted as long-run elasticities.

Interpretation of results (GMM in system)

In the five models (1, 2, 3, 4 and 5) of Table 6, the probabilities associated with the Hansen tests are greater than 5%, which means that the instruments are overall exogenous, in other words the instruments used in the regressions are valid. Furthermore, the probability associated with the second-order autocorrelation test is also greater than 5%, therefore the hypothesis of second-order autocorrelation, AR (2), can also be rejected. The observation of the statistics therefore shows that the condition of non-correlation is satisfied and the dynamic model in panel data used is good. The ratio between the number of individuals (group or country) and the number of instruments is greater than 1 in the different models.
Regarding the estimation results, model (1) represents the results obtained using the Squalli & Wilson (2011) indicator as a proxy for overall real openness. On the other hand, model (2) represents the results obtained when trade openness is captured by the traditional indicator (the sum of exports and imports reported to GDP).

Table 6. Summary of results: first GMM-Sys estimation

CO2 emission	Model 1	Model 2	Model 3	Model 4	Model 5
CO_{2t-1}	0.857**	0.987**	0.327***	0.964**	0.743**
	(1.36)	(1.44)	(1.97)	(1.02)	(1.07)
Global real opening	0.161**	0.194	0.051***	0.102**	0.117***
	(0.54)	(0.55)	(0.71)	(0.98)	(0.32)
GDP/h (Scale effect)	0.010***	0.011**	0.021**	0.087**	0.093***
	(0.89)	(0.93)	(0.44)	(0.24)	(0.53)
GDP^2/h (Technical effect)	-0.014***	-0.027**	-0.113**	-0.009**	-0.021
	(0.11)	(0.37)	(0.09)	(0.31)	(0.81)
Physical Capital	0.038***	0.078**	0.337**	0.781**	0.018
	(0.66)	(0.91)	(1.25)	(0.57)	(0.29)
Human Capital	0.071**	0.210	0.023	0.831**	0.711
	(0.47)	(0.11)	(0.80)	(0.87)	(0.24)
Financial Dev.	-0.007	-0.008	0.222**	-0.001	0.003
	(0.77)	(0.20)	(0.90)	(0.73)	(0.74)
Energy Re	-0.782**	-0.982***	-0.966***	-0.666**	-0.358***
	(1.72)	(1.82)	(1.73)	(1.28)	(1.91)
Population	0.004**	0.0001	0.444***	0.003	0.009
	(0.88)	(1.66)	(1.02)	(1.07)	(1.01)
Governance	0.875**	0.002**	0.336***	0.563**	0.552
	(0.86)	(0.84)	(1.52)	(1.69)	(1.55)
Constant	9.002**	4.421**	1.853**	3.002**	6.331**
	(1.22)	(1.72)	(1.43)	(1.03)	(0.78)
Observations	684	586	683	683	684
Groups	38	38	38	38	38
Instruments	31	26	24	28	30
AR (1) p-value	0.000	0.000	0.000	0.000	0.000
AR(2) p-value	0.321	0.225	0.351	0.241	0.254
Hansen p-value	0.212	0.256	0.219	0.252	0.244

Source: Author from world bank data.

Note: Numbers in parentheses denote Student's t-scores in absolute values; *, ** and *** the significance at the 1%, 5% and 10% thresholds, respectively. Notations: models: 1. trade openness is captured by the Squalli & Wilson (2011) indicator; 2. trade openness is captured by the traditional indicator; 3. trade openness in the primary sector (agriculture); 4. trade openness in the secondary sector (sum of exports of manufactured goods and imports as a percentage of exports and imports of goods); 5. trade openness in the tertiary sector (trade in services as a percentage of gross domestic product*)*.

And finally, models 3, 4 and 5 represent the results obtained when the overall real openness is observed respectively in the primary sector (agriculture), the secondary sector (industry) and the tertiary sector (service). In the case of model (1), the hypothesis of the Kuznets environmental curve is verified (because GDP/h has a positive coefficient of 0.01, and its square has a negative coefficient of -0.014 and both are significant at 10%). This result corroborates those found by Hakimi & Hamdi (2019); Shahbaz & Sinha (2019); Sabir et *al*. (2020), To et *al*. (2019), Dauda et *al*. (2019), Emrah & Aykut (2018). This result is quite revealing, since unlike advanced countries, SSA

countries are at their early stage of development, and use less sophisticated techniques to reduce carbon emissions. This model shows that trade openness has a positive and significant effect at 5% on CO_2 emissions in SSA.
Indeed, a 1% increase in trade openness leads to a 0.16% increase in CO_2 emissions in SSA in the long term. Physical capital has a positive and significant coefficient at 10%. A 1% increase in gross fixed capital formation leads to a 0.038% increase in CO_2 emissions in SSA. This impact is significant in most models. And this result is contradictory to that found by Fauzel (2017) in Mauritius. This result shows that domestic investments in SSA do not take environmental issues into account. When the overall real openness is captured by the traditional indicator (model 2), the coefficient associated with openness remains positive (0.194) but not significant. This can be explained by the fact that this indicator does not truly capture the level of commercial openness of a country. Furthermore, this model shows that the scale effect has a positive and significant coefficient of the order of 0.01. Furthermore, the technical effect contributes as in model 1 to reducing CO_2 emissions in SSA.
When we look at the different sectors of the economy, trade openness in the primary sector (trade in agricultural goods as a percentage of goods) has a positive and significant effect at 10% on CO_2 emissions in SSA. Indeed, the results of model (3) show that a 1% increase in trade in agricultural products leads to a 0.051% increase in atmospheric pollution by CO_2 in SSA. These results can be explained by the different archaic techniques used in agriculture in most SSA countries. The coefficients associated with the scale and technical effects are of the order of 0.021 and -0.113 respectively. In the secondary sector (model 4), the overall real openness is captured by trade in manufactured goods, i.e. goods resulting from human activity based on raw materials. In this model, trade openness has a positive and significant impact at 5% on atmospheric pollution by CO_2 in SSA. Indeed, if the opening of trade in manufactured goods increases by 1%, CO_2 emissions increase by 0.102%.
In this sector, the scale effect has a positive coefficient (0.087) while the technical effect negatively affects (-0.009) CO_2 emissions in SSA. This can show that the positive effect of global openness on CO_2 emissions in SSA is due to activities in the industrial sector such as extractive industries, which have too lax environmental regulations. In model (5), trade openness is captured by trade in services. The associated coefficient is positive (0.117) and significant. This shows that this sector also influences CO_2 emissions in SSA. The signs of the theoretical channels of international trade (scale and technical effects) through which openness affects emissions respect the theoretical prediction. Furthermore, in all the results, the coefficient of renewable energy consumption remains negative and significant at 5%, 10%, 10%, 5% and 10% respectively for models 1, 2, 3, 4 and 5.
This shows overall that renewable energy consumption contributes significantly to reducing CO_2 emissions in SSA. Furthermore, there is mainly strong evidence that carbon emissions decrease with increasing use of renewable energy, as shown by Acheampong et *al.* (2019). These results strongly corroborate the empirical results of Dong et *al.* (2018) who found that renewable energy consumption plays an important role in mitigating carbon emissions. This suggests that the continued use of fossil energy (oil, gas and coal) for commercial purposes contributes to carbon emissions. In addition, and to some extent, the increasing use of non-renewable energy and the lack of substitutable energy in SSA seems to be the most important challenge to reduce global warming, a situation that calls for much attention. Therefore, our results show that greater consumption of renewable energy reduces CO_2 emissions in SSA.
Many of the empirical studies have explored the causal relationship between the use of renewable energy and CO_2 emissions (Toumi & Toumi, 2019; Nathaniel & Iheonu, 2019; Baloch et *al.* 2019; Waheed et *al.* 2018; Dong et *al.* 2018; Charfeddine et *al.* 2018). In all the results, it is also found that the increase in population growth leads to an increase in CO_2 emissions in SSA. Indeed, in the first model, the coefficient associated with population growth is positive and significant at 5% (0.004). This coefficient is also positive and significant at 10% (0.444) in Model 3. In the other models, the effect is positive and insignificant. Therefore, the increase in population in SSA contributes to air pollution. Acheampong et al. (2019) also found that population growth contributes to the increase in CO_2

emissions in SSA. Regarding financial development, its effect on carbon emissions in SSA is not pronounced in this study. Indeed, it has a positive coefficient in some models and negative in others, and none of the results are significant. This is necessarily due to the weakness of the financial sector in SSA.

In all models, our results revealed that institutional quality measured using the composite index (which includes six governance indicators: freedom of speech and accountability, political stability, state effectiveness, regulatory quality, rule of law and control of corruption) positively impacts CO_2 emissions in SSA. Indeed, governance has a positive and significant coefficient on CO_2 emissions in all models except model 5. This result can be explained by the poor application of governance dimensions in CO_2 mitigation in SSA. For example, corruption can influence subsidies received by companies or the level of trade protection. Corruption also indirectly affects emissions through its effect on income level (Cole, 2007). In model 1 and model 4, human capital positively and significantly impacts CO_2 emissions in SSA at 5%. The implication of this result is that the level of education is low in SSA, and the population is still unaware of environmental issues.

This result corroborates those of Dauda et a*l*. (2020) in African countries. Human capital has become an important element of CO_2 mitigation strategies over the years, as a certain level of education allows people to understand the importance of complying with environmental rules and the need to reduce CO_2 emissions. When certain actions such as vocational training, learning by doing, research and development are not taken into account, human capital activities can affect environmental CO_2 pollution. Furthermore, environmental policies are likely to be achieved in places where the level of education of citizens is moderately high because there is a tendency to obey environmental rules (Desha et *al*. 2015).

Robustness analysis 1: Reestimation by the system GMM

In this section, we will repeat the estimation of our study model using the GMM method, taking into account the institutional variable each time. The results are reported in Table 7 below. In the seven models (1, 2, 3, 4, 5, 6 and 7) in Table 7, the probabilities associated with the Hansen tests are greater than 5%, which means that the instruments are generally exogenous, in other words the instruments used in the regressions are valid. Furthermore, the probability associated with the second-order autocorrelation test is also greater than 5%, therefore the hypothesis of second-order autocorrelation, AR(2), can also be rejected. The observation of the statistics therefore shows that the condition of non-correlation is satisfied and the dynamic model in panel data used is good. Model 1 presents the results of the estimation when corruption and its interaction with openness are taken into account. In the same logic, political stability is taken into account in model 2; voice and accountability in model 3; government effectiveness in model 4; regulatory quality in model 5; rule of law in model 6 and the composite index in model 7.

In the seven models, trade openness positively impacts CO_2 emissions in SSA. This confirms the results obtained previously. The CEK hypothesis is also confirmed in all models in accordance with the previous results and the theoretical prediction. Furthermore, these results show that the weakness of institutions in SSA is a handicap for improving its environment. Indeed, the six indicators of institutional quality have a positive and significant effect on CO_2 emissions in SSA. For example, when corruption, voice and accountability, regulatory quality each increase by 1%, CO_2 emissions increase by 0.32%; 0.05%; 0.9% respectively in SSA. On the other hand, when trade openness interacts with a complementary policy, in this case the indicators of the quality of governance in the context of this work, the coefficient of the interaction remains negative. Indeed, the interaction gives negative coefficients (-0.002) for model 1; -0.002 for model 2; -0.0001 for model 3; -0.02 for model 4 and -0.75 for model 5, -0.54 for model 6, -0.01 for model 7. Consequently, for trade openness to improve the quality of the environment by reducing CO_2 emissions in SSA, it must be accompanied by effective institutions.

Table 7. Summary of results: second GMM-Sys estimation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				SYS-GMM			
VARIABLES				CO_2 emissions			
CO_{2t-1}	0.012**	0.452**	0.513**	0.836**	0.791**	0.215**	0.325**
	(0.0472)	(0.0321)	(0.0445)	(0.0258)	(0.0398)	(0.0142)	(0.0784)
Trade openness	0.193**	0.0369***	0.0114**	0.0235***	0.0714**	0.0321**	0.387**
	(0.447)	(0.00112)	(0.0714)	(0.2541)	(0.0147)	(0.0883)	(0.0892)
GDP/h (Scale effect)	0.111***	0.0216***	0.0601***	0.00944	0.0169***	0.0422***	-0.0155***
	(0.0854)	(0.2514)	(0.0105)	(0.0258)	(0.2780)	(0.00428)	(0.00630)
GDP^2/h (Technical effect)	-0.0177**	-0.0315***	-0.0875***	-0.0782**	-0.0981***	-0.0410*	-0.0108***
	(0.0143)	(0.000801)	(0.00808)	(0.00821)	(0.00841)	(0.00983)	(0.00347)
Physical Capital	0.0247	0.7412***	1.0008***	0.7360***	0.888***	1.0014***	1.0082***
	(0.677)	(0.641)	(0.819)	(0.398)	(0.401)	(0.442)	(0.871)
Human Capital	0.2221**	0.1009***	0.00007***	0.0014*	0.215***	0.8214***	0.3671*
	(0.012)	(0.7210)	(0.0418)	(0.0214)	(0.0014)	(0.2170)	(0.07618)
Financial Development	-0.3325	0.214	0.6020	0.01408	-0.0218	-0.4436	-0.8754
	(0.362)	(0.0325)	(0.0711)	(0.0896)	(0.0451)	(0.0963)	(0.0321)
Renewable Energy	-0.2314**	-0.2143***	-0.0047*	-0.0001*	-0.00008**	-0.0214**	0.302***
	(0.134)	(0.00459)	(0.0237)	(0.0420)	(0.0304)	(0.0240)	(0.0539)
Population	0.0021***	0.0361	0.0702	0.0014**	0.0961***	0.5551	0.0122***
	(0.135)	(0.0752)	(0.00441)	(0.00652)	(0.00375)	(0.00273)	(0.00523)
Corruption	0.328***	0.00142***	0.0114***	0.0043**	0.00258***	0.00871*	0.0102***
	(1.113)	(0.025)	(0.023)	(0.054)	(0.0021)	(0.0045)	(0.0521)
Trade openness # C. Corruption	-0.0025**						
	(0.145)						
Political Stability		0.211***					
		(0.821)					
Trade openness*Political Stability		-0.0021***					
		(0.0011)					
Voices and responsability			0.0541				
			(0.233)				
Trade openness*Voices and responsability			-0.0001***				
			(0.2141)				
government effectiveness				0.823			
				(0.058)			
Trade openness* government effectiveness				-0.0214***			
				(0.002)			
Regulatory Quality					0.981***		
					(0.251)		
Trade openness *Regulatory Quality					-0.7512		
					(0.0452)		
Rules of law						1.0008***	
						(0.814)	

Trade openness *Rules of law						-0.541 (0.144)	
Composite Governance Index							0.410*** (0.0766)
Trade openness* Composite Governance Index							-0.0140*** (0.0724)
Constant	1.52*** (2.104)	3.752*** (1.741)	5.413*** (1.485)	7.012*** (2.441)	3.113*** (2.783)	10.220*** (2.879)	7.069*** (2.331)
Observations	683	681	675	679	684	683	684
Number of groups	38	38	38	38	38	38	38
Instruments	22	31	27	27	29	30	29
AR (1) p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AR (2) p-value	0.221	0.125	0.329	0.238	0.219	0.105	0.821
Hansen p-value	0.466	0.328	0.420	0.143	0.325	0.413	0.269
Notations **:** Numbers in parentheses denote Student's t-scores in absolute values; *, ** and *** the significance at the 1%, 5% and 10% thresholds, respectively.							

Source: author from world bank data

Robustness Analysis 2: Estimation by the Ordinary Double Least Squares Method

In this section, we re-estimate the effects of trade openness on CO_2 emissions using the instrumental variables approach with the ordinary double least squares method. The results of the estimations without and with control variables are reported in Table 8. The tests confirm the validity of the instruments. Indeed, in the seven models (1, 2, 3, and 4) in Table 8, the probabilities associated with the Hansen tests are greater than 5%, which means that the instruments are overall exogenous, in other words the instruments used in the regressions are valid. Therefore, the absence of rejection of the null hypothesis in the Hansen test confirms the validity of the instruments. In addition, the Fisher statistic for each specification is greater than 10.

The under-identification test (KP-LM) is statistically good since it is of the order of 0.000 for all specifications. The Hansen statistic corroborates the results given by the coefficients of determination and the KP-LM probability. Finally, the F-stats give values greater than 10 for the different specifications signifying the good quality of the result. We conclude that the model is statistically validated.

Table 8. The effects of trade openness on CO_2 emissions: Ordinary Double Least Squares Method

	DEPENDENT VARIABLE : CO_2 EMISSION			
VARIABLES	(1)	(2)	(3)	(4)
TRADE OPENNESS	1,87***	0,31***	0,092**	0,011**
	(0,027)	(0,029)	(0,292)	(0,023)
GDP/H		0,210*	0,211***	0,206***
		(0,011)	(0,022)	(0,031)
GDP^2/H		-0,021***	-0,038	-0,035***
		(0,021)	(0,015)	(0,028)
PHYSICAL CAPITAL		0,025***	0,021**	0,001*
		(0,041)	(0,020)	(0,009)
HUMAN CAPITAL		0,001	0,005	-0,035**
		(0,054)	(0,019)	(0,033)
FINANCIAL.DEV		0,004***	-0,007	0,009**
		(0,017)	(0,016)	(0,041)
RENEWEBLE. ENER			-0,359***	-0,097***
			(0,057)	(0,037)
POPULATION			0,007***	0,041***
			(0,081)	(0,091)
GOVERNANCE				-0,127**
				(0,043)
CONSTANT	4,021*	4,254*	4,012*	3,968***
	(0,144)	(0,321)	(0,211)	(0,201)
OBSERVATIONS	684	684	684	684
R^2	0,119	0,171	0,133	0,152
KP-LM (P-VALUE)	0,000	0,000	0,000	0,000
HANSEN (P-VALUE)	0,325	0,582	0,655	0,758
F-STAT	451,7	605,4	359,8	584,6

Source: author from world bank data. **Note:** Robust standard deviations are reported in parentheses. * p<0,01, ** p<0,05, *** p<0,1

The results of model 1 (first column) of our estimation only retain trade openness as the explanatory variable, which can lead to a question of omission of explanatory variables arbitrarily inflating the expression of the coefficient of this variable. We will objectively interpret the coefficients of the last two columns which contain the maximum of explanatory variables. We will first proceed to the interpretation of the variable of interest and will follow that of the control variables. The variable of interest here is trade openness. This variable has the economically expected sign. Indeed, a one-point increase in trade openness leads, all other things being equal, to an increase of 0.092 points (column 3) or an increase of 0.011 (column 4) in the CO2 emissions rate. This result confirms the results previously obtained via the GMM method in system. Similarly to Sabir et *al.* (2020), the EKC hypothesis is verified for models 3 and 4. Indeed, GDP per capita has a positive and significant impact on CO_2 emissions while its square negatively affects CO_2 emissions.

Also focusing on the other control variables, we observe that they have overall the signs obtained in the GMM estimations. For example, the positive sign of human capital in model 3, the positive sign of population in models 3 and 4, the negative sign of renewable energy consumption, the negative sign of institutional quality and the positive sign of physical capital.

Conclusions and Policy implications

Through an original and innovative measure this study has to evaluate the effects of trade openness on CO_2 emissions in SSA. Through stylized facts, this study analyzed the trade performance, CO_2 emissions and export breakdown of SSA countries. The analysis of CO_2 emissions shows that in SSA, the emission rate is increasing over the period 2005-2022 despite its low contribution to global emissions. In addition, the breakdown of exports shows that this region is increasingly integrated into international trade. This study presented the methodology, results and interpretations. The indicator of Squalli & Wilson (2011) is used to capture the degree of openness of SSA countries. Through the GMM method and the robustness by the Ordinary Double Least Squares Method, the results showed that the estimation methods are unanimous on the positive effect of trade opening on CO_2 emissions. In terms of elasticity, the 1% increase in trade openness results in a 0.16% increase in CO_2 emissions in ASS. The arguments put forward include that trade increases the intensity of fossil energy consumption through the export of goods and services, which makes the industrial sector heavily dependent on fossil energy. The effect is that CO_2 emissions increase as economies tend to accumulate trade surpluses through exports. This study validated the existence of the hypothesis of the environmental curve of Kuznets (because GDP/capita has a positive coefficient of 0.010, and its square has a negative coefficient of -0.0141 and both are significant). In addition, trade opening in different sectors of the economy has shown that the primary (agriculture) and secondary (industry) sectors and the tertiary (services) sector contribute to the increase in CO_2 emissions in SSA. The dynamic model is controlled by several variables. In all the results, it was found that renewable energy consumption contributes significantly to reducing CO_2 emissions in SSA. In addition, the effect of financial development on SSA carbon emissions is not pronounced in this study because no results are significant. This is necessarily due to the weakness of the financial sector in SSA. Institutional quality measured by the composite index (which includes six governance indicators such as freedom of speech and accountability, political stability, state effectiveness, quality of regulation, rule of law and control of corruption) positively impacts CO_2 emissions in SSA. Human capital has a positive and significant impact on CO_2 emissions in SSA. The implication of this finding is that education levels are low in SSA, and people are still unaware of environmental problems.

With the world's rapid climate change, policy makers in SSA are encouraged to develop strategies that improve environmental quality (by reducing CO_2 emissions). To do so, they must: Include the environment component in their agenda for future trade negotiations. Choosing business partners with an eye to their environmental commitment. They must implement policies and strategies that ensure growth without abandoning the environment. Implement strategies to exploit and develop its energy potential and, by extension, reduce CO_2 emissions. The SSA has many natural resources, such as the rainforest which is one of the main carbon sinks on the planet and a potential source of renewable energy. Act on human capital, because a certain level of education allows the population to understand the importance of respecting environmental rules and the need to reduce CO_2 emissions. To achieve this, certain actions such as vocational training, learning by doing and research and development must be taken into account; improving the quality of their institutions by implementing appropriate policies and strategies.

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References

Acheampong A.O., Samuel A. & Elliot B. (2019). Do globalization and renewable energy contribute to carbon emissions mitigation in Sub-Saharan Africa?. *Science of the Total Environment*, 677, 436-446.

Acheampong A.O. (2018). Economic growth, CO2 emissions and energy consumption: What causes what and where?. *Energy Economics*, 74, 677-692.

Adebanjo S. & Akintunde W.B. (2024). Exploring the link between technological innovation, economic development, and CO2 emissions in the US. Application of the ANN and EKC techniques. *Journal of Environmental Science and Economics*, ISSN: 2832-6032, https://doi.org/10.56556/jescae.v3i1.809.

Ahmed Z. & Wang Z. (2019). Investigating the impact of human capital on the ecological footprint in India: An empirical analysis. *Environmental Science and Pollution Research*, 26, 26782-26796.

Ali H.S., Law S.H., Lin W.L., Yusop Z., Chin L. & Bare U.A.A. (2019). Financial development and carbon dioxide emissions in Nigeria: evidence from the ARDL bound approach. *GeoJournal*, 83, 641-655.

Andriamahery A., Danarson J. & Qamruzzaman Md. (2022). Nexus between trade and environmental quality in sub-saharan Africa: Evidence from panel GMM. *Frontiers in Environmental Science*, 10. 10.3389/fenvs.2022.986429.

Antweiler W., Copeland B.R. & Taylor M.S. (2001). Is free trade good for the environment?. *American Economic Review,* 914, 877-908.

Arellano M. & Bover O. (1995). Another look at the instrumental variable estimation of error-components models. *Journal of Econometrics,* 68, 29-51.

Arminen H. & Menegaki A.N. (2019). Corruption, climate and the energy-environment-growth nexus. *Energy Economics*, 80, 621-634.

Asif R. (2024). Influences of foreign direct investment and carbon emission on economic growth in Vietnam, *Journal of Environmental Science and Economics.* https://doi.org/10.56556/jescae.v3i1.670.

Avom D., Nkengfack H., Fotio H.F. & Totouom A. (2020). ICT and environmental quality in Sub-Saharan Africa: Effects and transmission channels. *Technological Forecasting and Social Change,* 155,120028.

Awad A. (2019). Does economic integration damage or benefit the environment? Africa's experience. *Energy Policy,* 132, 991-999.

Aydin M. & Turan Y.E. (2020). The influence of financial openness, trade openness, and energy intensity on ecological footprint: revisiting the environmental Kuznets curve hypothesis for BRICS countries. *Environmental science and pollution Research,* 27, 43233-43245.

Baloch M.A., Mahmood N. & Zhang J.W. (2019). Effect on natural resources, renewable energy and economic development on CO2 emissions in BRICS countries. *Science of the Total Environment,* 678-632-638.

Balsalobre-Lorente D., Shahbaz M., Roubaud D. & Farhani S. (2018). How economic growth, renewable electricity and natural resources contribute to CO2 emissions?. *Energy Policy*, 113, 356-367.

Barkat K., Mouyad A., Al Kwifi O.S. & Shaif J. (2024). Does trade openness mitigate environmental damage in Organisation for Economic Co-operation and Development (OECD) countries? Implications for achieving sustainable development, *Natural Resources Forum*, https://doi.org/10.1111/1477-8947.12412.

Bouchoucha N. (2024). Does Trade Openness and Environmental Quality Matter for Health Status? Evidence from African Countries. *J Knowl Econ,* 15, 5729-5745. https://doi.org/10.1007/s13132-023-01197-w.

Brenton P. & Chemutai V. (2021). The trade and climate change nexus: the urgency and opportunities for developing countries, World Bank, Washington DC.

Cai Y., Chang T. & Inglesi-Lotz R. (2018). Asymmetric persistence in convergence for carbon dioxide emissions based on quintile unit root test with Fourier function. *Energy*, 161,470-481.

Charfeddine L., Al-Malk A. & Korbi K. (2018). Is it possible to improve environmental quality without reducing economic growth: Evidence from the Qatar economy. *Renewable and Sustainable Energy Reviews,* 82, 25-39.

Chatri A., Zouiri H., Zenati A. & Chouati M. (2019). *Trade openness, human capital accumulation and growth: panel data analysis on developing countries. In A. Chatri (ed). Openness, productivity and economic growth in Morocco, Laboratory of Applied Economics & Policy Center for the New South. Rabat.*

Chen F., Jiang G. & Kitila M.G. (2021). Trade Openness and CO2 Emissions: The Heterogeneous and Mediating Effects for the Belt and Road Countries. *Sustainability*, *13*, 1958.

Chhabra M., Giri A.K. & Kumar A. (2023). Do trade openness and institutional quality contribute to carbon emission reduction? Evidence from BRICS countries. *Environmental Scieence and Pollution Research*, 50986-51002. https://doi.org/10.1007/s11356-023-25789-w.

Chirambo D. (2018). Towards the achievement of SDG 7 in sub-Saharan Africa: Creating synergies between Power Africa, Sustainable Energy for All and climate finance in-order to achieve universal energy access before 2030. *Renewable and Sustainable Energy Reviews,* 94, 600-608.

Cole M.A. (2007). Corruption, income and the environment: an empirical analysis. *Ecological Economics,* 62, 637-647.

Coskuner C., Paskeh M.K., Olasehinde-Williams G. & Akadiri S.S. (2020). Economic and social determinants of carbon emissions: Evidence from organization of petroleum exporting countries. *Journal of Public Affairs*, 20, e2092.

Dauda L., Xingle L., Mensah C.N. & Salman M. (2019). The effects of economic growth and innovation on CO2 emissions in different regions. *Environmental Science and Pollution Research,* 26, 15028-15038.

Dauda L, Xingle L., Mensah C.N., Salman M., Boamah K.B., Ampon-Wireko S. & Dogbe K.C.S, (2020). Innovation, trade openness and CO2 emissions in selected countries in Africa. *Journal of Cleaner Production,* 281, 125143.

Desha C., Robinson D. & Sproul A. (2015). Working in partnership to develop engineering capability in energy efficiency. *Journal of Cleaner Production,* 106, 283-291.

Dong K., Hochman G., Zhang Y., Sun R., Li H. & Liao H. (2018). CO2emissions, economic and population growth, and renewable energy: Empirical evidence across regions. *Energy Economics,* 75, 180-192.

Dou Y., Chen F., Kong Z. & Dong K. (2023). Re-estimating the trade openness-carbon emissions nexus: a global analysis considering nonlinear, mediation, and heterogeneous effects. *Applied Economics*, *55*(57), 6793-6808.

Du K., Yu Y. & Li J. (2020). Does international trade promote CO2 emission performance? An empirical analysis based on a partially linear functional-coefficient panel data model. *Energy Econ*, 92:104983.

Duodu E. & Mpuure D.M-N , (2023). International trade and environmental pollution in sub-Saharan Africa: do exports and imports matter ?. *Environmental Science and Pollution Research* ,30,53204-53220.

Duodu E., Kwarteng E., Oteng-Abayie EF. & rimpong PB. (2021). Foreign direct investments and environmental quality in sub-Saharan Africa: the merits of policy and institutions for environmental sustainability. *Environmental Science and Pollution Research,* 28, 66101.66120.

Efobi U., Tanankem B., Orkoh E., Atata S. N., Akinyemi O. & Beecroft I. (2019). Environmental Pollution Policy of Small Businesses in Nigeria and Ghana: Extent and Impact. *Environmental Science and Pollution Research,* 26, 2882-2897.

Ehigiamusoe K.U., Lean H.H. & Smyth R. (2020). The Moderating Role of Energy Consumption in the Carbon Emissions-Income Nexus in Middle-Income Countries. *Applied Energy. 261, 114215. doi:10.1016/j.apenergy.2019.114215*

Emma S.O. (2024). An econometric study of eco-innovation, clean energy, and trade openness toward carbon neutrality and sustainable development in OECD countries. *Sustainable Development,* 32,4, August, Pages 3075-3099.

Emrah K. & Aykut Ş. (2018). The impact of foreign direct investment on CO2 emissions in Turkey: new evidence from cointegration and bootstrap causality analysis. *Environmental Science and Pollution Research International,* 25,790-804.

Essandoh O.K., Islam M. & Kakinaka M. (2020). Linking international trade and foreign direct investment to CO2 emissions: Any differences between developed and developing countries?. *Science of The Total Environment,* 712, 136437.

Ewane E. B. & Ewane E.I. (2023). Foreign Direct Investment, Trade Openness and Environmental Damage in SSA Countries. A Quadratic Modeling and Turning Point Approach. *American Journal of Environmental Economics,* https://doi.org/10.54536/ajee.v2i1.1414.

Fauzel S. (2017). The impact of FDI on CO2 emission in a small island developing state: A cointergration approach. *Economics and Business Letters,* 61, 6-13.

Ganda F. (2021). The influence of growth determinants on environmental quality in Sub-Saharan Africa states. *Environment, Development and Sustainability*. 23,7117-7139.

Ghaderi Z., Saboori B. & Khoshkam M. (2023). Revisiting the Environmental Kuznets Curve Hypothesis in the MENA Region: The Roles of International Tourist Arrivals, Energy Consumption and Trade Openness. *Sustainability*, 15, 2553. https://doi.org/10.3390/ su15032553.

Gnangnon S. K. (2020). Trade openness and diversification of external financial flows for development: An empirical analysis. *South Asian J. Macroecon. Public Finance*, 9, 22-57.

Goswami A., Kapoor H.S., Jangir R.K., Ngigi C.N., Nowrouzi-Kia B. & Chattu V.K. (2023). Impact of Economic Growth, Trade Openness, Urbanization and Energy Consumption on Carbon Emissions: A Study of India. *Sustainability*, 15, 9025. https://doi.org/10.3390/ su15119025.

Gräbner C., Heimberger P., Kapeller J. & Springholz F. (2021). Understanding economic openness: a review of existing measures. *Review of World Economics*, 157, 87-120.

Grossman G.M. & Krueger A.B. (1993). Economic Growth and the Environment. *Quarterly Journal of Economics*, 110, 353-377.

Habib S., Abdelmonen S. & Khaled M. (2020). The effect of corruption on the environmental quality in African countries: A panel quintile regression analysis. *Journal of the Knowledge Economy*, 11, 788-804.

Hakimi A. & Hamdi H. (2016). Trade Liberalization, FDI Inflows, Environmental Quality and Economic Growth: a Comparative Analysis Between Tunisia and Morocco. *Renewable and Sustainable Energy Reviews*, 58, 1445-1456.

Hakimi A. & Hamdi H. (2020). Environmental effects of trade openness: what role do institutions have?. *Journal of Environmental Economics and Policy*, 9,36-56.

Hariyani H.F., Prasetyo D.G., Ha T.T.V. et *al*. (2024). Unlocking CO2 emissions in East Asia Pacific-5 countries: Exploring the dynamics relationships among economic growth, foreign direct investment, trade openness, financial development and energy consumption. *Journal of Infrastructure, Policy and Development*. 8(8): 5639. https://doi.org/10.24294/jipd.v8i8.5639.

Haseeb A., Xia E., Baloch A.M. & Abbas K. (2018). Financial development, globalization, and CO2 emission

Haseeb A., Xia E., Saud S., Usman M. & Quddoos M.U. (2023). Unveiling the liaison between human capital, trade openness, and environmental sustainability for BRICS economies: Robust panel-data estimation, *Natural Resources Forum*, https://doi.org/10.1111/1477-8947.12277.

in the presence of EKC: evidence from BRICS countries. *Environmental Science and Pollution Research*, 25, 31283-31296.

Hu H., Nan X., Debin F. & Xiaoling Z. (2018). The role of Renewable Energy Consumption and commercial services trade in carbon dioxide reduction: Evidence from 25 developing countries. *Applied energy*, 211, 1229-1244.

Huang Y., Chen F., Wei H., Xiang J., Xu Z. & Akram R. (2022). The Impacts of FDI Inflows on Carbon Emissions: Economic Development and Regulatory Quality as Moderators. *Front Energy Research*. 9:820596. doi: 10.3389/fenrg.2021.820596

Ibrahim RL. & Ajide KB. (2022). Trade facilitation and environmental quality: empirical evidence from some selected African countries. *Environment Development and Sustainability*, 24, 1282-1312.

Iheonu C.O., Anyanwu O.C., Odo O.K. & Nathaniel S.P. (2021). Does economic growth, international trade, and urbanization uphold environmental sustainability in sub-Saharan Africa? Insights from quantile and causality procedures. *Environment Science Pollution Research*, 28, 28222-28233.

Inglesi-Lotz R. (2018). Decomposing the South African CO2 emissions within a BRICS countries context: signaling potential energy rebound effects. *Energy*, 147, 648-654.

Inglesi-Lotz R. & Dogan E. (2018). The role of renewable versus non-renewable energy to the level of CO2 emissions a panel analysis of sub-Saharan Africa's Big 10 electricity generators. *Renewable Energy,* 123, 36-43.

IPCC (2021). Climate Change 2022: Mitigation of Climate Change. Genève, Suisse, 175 pages.

Junaid A., Zeeshan A. & Aiman J. (2023). The spatial spillover effects of energy transition and trade openness on CO2 emissions, *Energy and Buildings*, https://doi.org/10.1016/j.enbuild.2023.113167.

Kalayci C. & Hayaloglu P. (2019). The Impact of Economic Globalization on CO2 Emissions: The Case of NAFTA Countries. *International Journal of Energy Economics and Policy,* 9, 356-360.

Kim D.H., Suen Y.B. & Lin S.C. (2019). Carbon dioxide emissions and trade: evidence from disaggregate trade data. *Energy Economics*, 78, 13-28.

Kwakwa P. A. (2023). Climate change mitigation role of renewable energy consumption: Does institutional quality matter in the case of reducing Africa's carbon dioxide emissions? *Journal of Environmental Management*, 342, 118234.

Kwakwa P.A., Alhassan H. & Adu G. (2020). Effect of natural resources extraction on energy consumption and carbon dioxide emission in Ghana. *International Journal of Energy Sector Management,* 10, 20-39.

Lemaallem H., & Outtaj B. (2023). Impact of commercial and financial openness on economic growth: What short- and long-term dynamics? *Alternatives Managériales Economiques,* 5, 375-396.

Liu L., Anwar A., Irmak E. & Pelit I. (2022a). Asymmetric linkages between public-private partnership, environmental innovation, and transport emissions. *Econ Res,* 35,6519-6540

Maku O.A. & Ikpuri O.P. (2020). A Multivariate Analysis between Renewable Energy, Carbon Emission and Economic Growth: New Evidences from Selected Middle East and North Africa Countries. *International Journal of Energy Economics and Policy,* 10, 440-450.

Mapapu B. & Phiri A. (2018). Carbon emissions and economic growth in South Africa: a quantile regression analysis. *International Journal of Energy Economics and Policy,* 8, 195-202.

Mekuannet W.T. (2024). Review on Valuation of Environmental Amenity and Pollution. *Journal of Environmental Science and Economics*, ISSN: 2832-6032https://doi.org/10.56556/jescae.v3i2.837.

Mengal A., Mirjat N.H., DasWalasai G., Khatri S.A., Harijan K. & Uqaili M.A. (2019). Modeling of Future Electricity Generation and Emissions Assessment for Pakistan. *Processes*, 7, 212.

Mohsin R. (2024). Renewable energy adoption and CO2 emissions in G7 economies: In-depth analysis of economic prosperity and trade relations. *Journal of Environmental Science and Economics,* ISSN: 2832-6032, https://doi.org/10.56556/jescae.v3i2.839.

Muhammad S., Long X., Salman M. & Dauda L. (2020). Effect of urbanization and international trade on CO2 emissions across 65 belt and road initiative countries. *Energy* 196:117102.

Mutascu M. (2018). G7 countries: between trade openness and CO2 emissions. *Economics Bulletin*, 38, 1446-1456.

Nathaniel S.P. & Iheonu C.O. (2019). Carbon dioxide abatement in Africa: the role of renewable and non-renewable energy consumption. *Science of the Total Environment,* 679, 337-345.

Nguyen C.P., Schinckus C. & Dinh Su T. (2020). Economic integration and CO2 emissions: evidence from emerging economies. *Climate and Development,* 12, 369-384.

Ngwenya B., Oosthuizen J., Cross M., Frimpong K. & Chaibva C.N. (2018). A review of heat stress policies in the context of climate change and its impacts on outdoor workers: evidence from Zimbabwe. *International Journal of social Ecology and Sustainable Development,* 9, 1-11.

Nkengfack H., Fotio H.K. & Temkeng D.S. (2019). The Effect of Economic Growth on Carbon Dioxide Emissions in Sub-Saharan Africa: Decomposition into Scale, Composition and Technique Effects. *Modern Economy*, 10, 1398-1418.

Okelele DO., Lokina R. & Ruhinduka RD. (2022). Effect of trade openness on ecological footprint in sub-Saharan Africa. *African Journal of Economic Reviews, 10*, 209-233.

Omri E. & Saadaoui H. (2023). An empirical investigation of the relationships between nuclear energy, economic growth, trade openness, fossil fuels, and carbon emissions in France: fresh evidence using asymmetric cointegration. *Environ Sci Pollut Res*, 13224-13245. https://doi.org/10.1007/s11356-022-22958-1.

Pata U.K., Dam M.M. & Kaya F. (2023). How effective are renewable energy, tourism, trade openness, and foreign direct investment on CO_2 emissions? An EKC analysis for ASEAN countries. *Environmental Science and Pollution Research*, 14821-14837. https://doi.org/10.1007/s11356-022-23160-z.

Pham D. T. T. & Nguyen H. T. (2024). Effects of trade openness on environmental quality: evidence from developing countries. *Journal of Applied Economics*, 27(1). doi:10.1080/15140326.2024.2339610.

Ponce P., Alvarado R., Ponce K., Alvarado R., Granda D. & Yaguana K. (2019). Green returns of labor income and human capital: Empirical evidence of the environmental behavior of households in developing countries. *Ecological economics*, 160,105-113.

Potrafke N. (2015). The evidence on globalization. *World Economic*, 38, 509-552.

Qamruzzaman M. (2021). Nexus between environmental quality, institutional quality and trade openness through the channel of FDI: an application of common correlated effects estimation (CCEE), NARDL, and asymmetry causality. *Environ Sci Pollut Res Int*, 37,52475-52498.

Raza S. A. & Shah N. (2018). Impact of financial development, economic growth and energy consumption on environmental damage: evidence from Pakistan. MPRA Paper No. 87095, University Library of Munich, Germany.

Roodman D. (2009). How to do xtabond2: An introduction to difference and system GMM in Stata. *The Stata Journal*, 9, 86-136.

Sabir S., Qayyum U. & Majeed T. (2020). FDI and environmental damage: the role of political institutions in South Asian countries. *Environmental Science and Pollution Reserach,* 27, 32544-32553.

Salahuddin Md., Idris A.M., Nick V. & Jeff G. (2019). The effects of urbanization and globalization on CO2 emissions: evidence from the Sub-Saharan Africa (SSA) countries. *Environmental Science and Pollution Research*, 26, 2699-2709.

Santiago R., Alberto J. & Marques A.C. (2020). The impact of globalization and economic freedom on economic growth: the case of the Latin America and Caribbean countries. *Economic Change and Restructuring,* 53, 61-85.

Shahbaz M. & Sinha A. (2019). Environmental Kuznets curve for CO2 emissions: a literature survey. *Journal of Economics Studies,* 46, 106-168.

Sinha A. & Shahbaz M. (2018). Estimation of Environmental Kuznets Curve for CO2 emission: Role of renewable energy generation in India. *Renewable Energy*, 119, 703-711.

Solarin S.A., Al-Mulali U., Musah I. & Ozturk I. (2017). Investigating the pollution haven hypothesis in Ghana: An empirical investigation. *Energy,* 124, 706-719.

Sun H-P., Tariq G., Haris M. & Mohsin M. (2019). Evaluating the environmental effects of economic openness: evidence from SAARC countries. *Environmental Science and Pollution Research,* 26, 24542-24551.

Sun H., Samuel A.C., Yong G., Kai F. & Joshua C.K.A. (2019). Trade Openness and Carbon Emissions: Evidence from Belt and Road Countries. *Sustainability,* 11, 2682.

To H.A., Dao Ha T-T., Nguyen H.M. & Vo Hong D. (2019). The Impact of Foreign Direct Investment on Environment Damage: Evidence from Emerging Markets in Asia. *International Journal of Environmental Research and Public Health,* 16, 1636.

Toumi S. & Toumi H. (2019). Asymmetric causality among renewable energy consumption, CO2 emissions, and economic growth in KSA: evidence from a non-linear ARDL model. *Environmental Science and Pollution Research,* 26, 16145-16156.

Udeagha M.C. & Breitenbach M.C. (2023). On the asymmetric effects of trade openness on CO_2 emissions in SADC with a nonlinear ARDL approach. *Discov Sustain*, https://doi.org/10.1007/s43621-022-00117-3.

Udeagha M.C. & Ngepah N. (2019). Revisiting trade and environment nexus in South Africa: fresh evidence from new measure. *Environmental Science and Pollution Research,* 26, 29283-29306.

Usman O., Lorember P.T. & Olanipekun I.O. (2019). Revisiting the environmental Kuznets curve (EKC) hypothesis in India: the effects of energy consumption and democracy. *Environmental Science and Pollution Research,* 26, 13390-13400.

Waheed R., Chang D., Sarwar S. & Chen W. (2018). Forest, agriculture, renewable energy, and CO2 emission. *Journal of Cleaner Production,* 172, 4231-4238.

Wang Q., Zhang F. and Li R. (2024). Free trade and carbon emissions revisited: The asymmetric impacts of trade diversification and trade openness, *Sustainable Development,* 32, 1, February, Pages 876-901, https://doi.org/10.1002/sd.2703.

World Bank (2023). World Government Indicator. http://data.worldbank.org/data-catalog.

Word Bank (2023). World development indicators. World Bank, Washington DC.

Yameogo C.E.W., Omojolaibi J.A. & Dauda R.O.S. (2021). Economic globalisation, institutions and environmental quality in Sub-Saharan Africa. *Research in Globalization*, 3,100035.

Zakari A. & Tawiah V. (2019). Impact of Electricity Consumption, Financial Development, Trade Openness on CO2 Emissions: Evidence from Nigeria. *Economic Studies journal,* 4, 143-157.

Zamil A.M.A., Furqan M. & Mahmood H. (2019). Trade openness and CO2 emissions nexus in Oman. *Enterpreunership and Sustainability,* 7, 1319-1329.

Zheng S., Wang R., Mak T. M. W., Hsu S.-C. & Tsang D. C. W. (2021). How Energy Service Companies Moderate the Impact of Industrialization and Urbanization on Carbon Emissions in China?. *Science of the Total Environment,* 751, 141610. doi:10.1016/j.scitotenv.2020.141610