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RESEARCH ARTICLE

Toward a sustainable development in sub-Saharan Africa: do economic complexity and renewable energy improve environmental quality?

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Abstract

Emission reduction has become more crucial for environmental sustainability in light of the growing concerns about climate change. Many studies have identified that structural change and clean energy technologies improve environmental quality. However, there is an absence of empirics that focus on the sub-Saharan Africa (SSA) context, which shifted the structure of their economies from the agriculture sector towards sophisticated manufacturing activities that affect the environment. Hence, this study aims to investigate the impacts of economic complexity and renewable energy consumption on carbon emissions in 41 SSA countries between 1999 and 2018. The study adopts contemporary heterogeneous panel approaches to overcome heterogeneity and cross-sectional dependence issues that usually arise in panel data estimates. The empirical findings of the pooled mean group (PMG) cointegration analysis indicate that renewable energy consumption alleviates environmental pollution in the long run and short run. In contrast, economic complexity improves environmental quality in the long run but not in the short run. On the other hand, economic growth contributes adversely to environmental degradation in the long run and short run. The study indicates that urbanization worsens environmental pollution in the long run. In addition, the outcomes of the Dumitrescu–Hurlin panel causality test indicate a unidirectional causal path from carbon emissions to renewable energy consumption. The causality results also suggest that carbon emission has bidirectional causation with economic complexity, economic growth, and urbanization. Therefore, the study recommends that SSA countries change their economic structure towards knowledge-intensive production and adopt policies that encourage investment in renewable energy infrastructures by subsidizing the initiatives to achieve clean energy technologies.

Keywords Economic complexity · Renewable energy consumption · CO_2 emissions · Sub-Saharan Africa · Sustainable development

Abbreviations

ECI	Economic complexity index
REC	Renewable energy consumption
PMG	Pooled mean group
DOLS	Dynamic modified ordinary least squares
FMOLS	Fully modified ordinary least squares
SSA	Sub-Saharan Africa
CO_2	Carbon dioxide emissions
GHG	Greenhouse gas
CADF	Cross-sectional ADF
CIPS	Augmented cross-sectional IPS
ARDL	Autoregressive distributed lag
MMQR	Method of moments quantile regression
URB	Urbanization
EKC	Environmental Kuznets Curve

Introduction

In order to boost growth while preserving the environment, many developing economies critically need structural transformation. The demand for more industrialized goods is growing to meet the fierce global competition (Neagu 2019). Accordingly, the exports of highly sophisticated products are related to increased energy consumption, which inevitably increases energy intensity and environmental pollution (Neagu 2019; Pata 2021). In general, increased complexity

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levels indicate the level of the country's productive capacity, which corresponds to higher energy requirements (Sweet and Maggio 2015). Complex products need to be manufactured in very energy-intensive industrial bases, which may negatively influence the environment (Rafique et al. 2022). It is noteworthy that environmentally damaging industrial structures are mostly found in low-income nations that produce less sophisticated items (Rothman 1998). According to Doğan et al. (2019), the environment deteriorates when the country produces less sophisticated goods. Consequently, the increasing consumption of greenhouse gasses poses a threat to the environment, including climate change, global warming, and biodiversity loss (Pata 2021). To mitigate the consequences of environmental pollution, numerous meetings, including the Paris Agreement, the Montreal and Kyoto Protocols, and the Stockholm Conference, were held to be taken the appropriate actions. The implementation of structural change policies is necessary to transform the countries from the use of more energy-intensive towards energy-efficient technologies that lower CO_2 emissions (Shahzad et al. 2021).

The economic complexity index (ECI), initially introduced by Hausmann and Klinger (2006), aims to illustrate a country's capabilities to develop and export more complicated goods and quantifies the amount of productive knowledge ingrained in a nation. These capabilities are non-tradable inputs necessary for producing goods such as infrastructure, property rights, institutional quality, and human and physical capital (Hidalgo et al. 2007; Hidalgo and Hausmann 2009). The ECI indicator discovers that a country's production structure is subject to its level of knowledge accumulation and skilled labor. Complex economies require gathering relevant knowledge across large networks of people to develop and export more products, which only a few diverse nations can also export. However, less sophisticated economies have a limited basis of productive knowledge and produce ubiquitous goods requiring small knowledge networks (Neagu 2019). Furthermore, Hausmann et al. (2007) identified that economic complexity is connected with countries' income levels and that variations in their capabilities predict future economic growth. Notwithstanding that it is part of economic growth, economic complexity relates to environmental quality. The country's degree of complexity is reflected by its manufacturing structure that requires the use of energy resources, which could harm the environment by producing polluting components (Shahzad et al. 2021).

A firm economic complexity with accumulated productive capabilities could be achieved through a structural transformation, which moves emerging economies from the production of agricultural goods to more sophisticated industrial goods (Bhorat et al. 2019; Hausmann and Hidalgo 2011). Initially, the rise of economic complexity is predicted to increase the level of CO_2 emissions in low- and middle-income nations until they implement structural changes and accumulate their productive knowledge (Doğan et al. 2019). Likewise, Neagu and Teodoru (2019) point out that more intensive economic complexity might result in higher pollution that induces environmental damage. However, when a higher level of economic complexity is achieved, usually by the advanced nations, the amount of CO_2 emission drops (Can and Gozgor 2017). A more complex economy provides a platform for knowledge and skill-based manufacturing that improves environmental quality via the adoption of eco-friendly technologies (Hausmann et al. 2014). The rise in complexity postulates the knowledge and technology required for economies to become greener, such as the manufacture of energy-efficient products, the creation of energy from renewable sources, and innovations (Doğan et al. 2019). When the complexity level ultimately reaches this point, the environmental deterioration will start to slow. In addition, Neagu and Teodoru (2019) demonstrated that economic complexity is associated with technological advancement that creates not only sophisticated products but also energy-efficient industrial technologies. Moreover, economic complexity lowers carbon emissions in developed countries due to their structural changes, which shift from energy-intensive activities to technology-intensive production (Can and Gozgor 2017; Swart and Brinkmann 2020). The more sophisticated industrial economies emphasize investments in research and development to achieve cleaner technologies (Laverde-Rojas et al. 2021).

Sub-Saharan Africa (SSA) nations are transforming from reliance on agriculture-based exports to more complex industrial production, which requires more energy consumption. In the past decade, most of the countries in SSA that achieved considerable economic growth were resource-dependent economies (Bhorat et al. 2019). However, several nations, particularly in East Africa, have switched from low-productivity subsistence agriculture towards manufacturing activities. The agricultural value-added and employment are declining throughout the continent, although the scale of industrialization is not enough to lead to a higher growth rate (Carmignani and Mandeville 2014). Industrialization and economic growth could be accomplished at a cost to the environment (Attiaoui et al. 2017). Additionally, Wang et al. (2016) noted that a sizable portion of the workforce migrated from agriculture to urban-based industrial activities, which might intensify the adverse environmental effects. However, the use of green investments and renewable energy sources is regarded as a possible way to mitigate environmental damage (Hassan et al. 2022; Sharif et al. 2019; Wan et al. 2022). Rafique et al. (2022) argue that increasing investment in renewables and the efficient use of human capital will eventually boost economic complexity and environmental sustainability in both developed and developing countries.

According to the International Energy Outlook, worldwide energy consumption will have significantly grown by 2025, with fossil fuels accounting for between 80 and 95% of it. Hanif (2018) identified that fossil fuels are the primary fuel used to fulfill energy needs in most SSA countries because it contributes significantly to their economic growth. The massive use of non-renewable energy has resulted in catastrophic repercussions to the ecosystem (Pata 2021). Because of the topography and the high degree of sensitivity of its agricultural output, many SSA nations are vulnerable to climate change (Abdi et al. 2022; Ali Warsame and Hassan Abdi 2023). Inaction on climate change is expected to result in a 70% increase in CO_2 emissions by 2050, which multiplies the harmful consequences of anthropogenic GHG emissions (Pomázi 2012). In extreme cases, nearly half a million people die in sub-Saharan Africa each year due to air pollution alone (World Health Organization 2016). The recent COP27 promotes climate technology solutions for emerging economies to mitigate global environmental hazards. Warsame et al. (2022) suggest boosting the production and consumption of clean energy technology to enhance environmental sustainability. Besides, Lee (2019) acknowledged that using alternative energy sources and technologies often helps achieve sustainable development.

The world's biggest renewable energy sources can be found in Africa (Attiaoui et al. 2017). The continent offers sufficient solar radiation throughout the year and has the potential for geothermal and hydroelectric energy production. Scientists concur that wind energy might be extensively used. Despite having rich renewable energy resources, including solar, wind, hydropower, and enormous geothermal energy, many SSA nations only utilize a small portion of these (Warsame et al. 2022). This might be linked to the lack of technological developments in these countries to diversify their energy sources. Technical innovation might support accomplishing the goals of low-carbon economies and greener growth (Adebayo et al. 2022; Doğan et al. 2019). The process of structural change promotes eco-friendly techniques that will result in new products, improved procedures, and cleaner services (Lapatinas et al. 2019). The shift in a country's production structure opens up opportunities for highly productive activities, the manufacturing of greener goods, and the development of environmentally friendly technologies (Neagu and Teodoru 2019). According to Fotis and Polemis (2018), boosting the use of new technologies would result in more efficient energy consumption and promote renewable energy use in EU nations. Many studies have agreed that using renewable energy could promote environmental sustainability and expand growth in developing economies (Azam et al. 2021; Saidi and Omri 2020).

Even though the significance of productive capabilities and alternative energy sources for alleviating environmental pollution, there is an absence of studies that investigated the sub-Saharan Africa context. To fill this gap in the literature, the main objective of the study is to examine the role of economic complexity, renewable energy consumption, economic growth, and urbanization on carbon emissions using panel data between 1999 and 2018. Hence, this research contributes to the expanding body of knowledge in the following ways. Firstly, the study provides the first empirical evidence of the effects of economic complexity on carbon emission in sub-Saharan Africa. The study sheds light on how structural transformation affects the environment. Secondly, the few studies that investigated the phenomenon in various regions did not consider the effects of urbanization on the environmental pollution-renewable-economic complexity nexus. Since SSA is among the fastest urbanizing regions in the world, the research jointly analyzes how economic complexity, renewable energy sources, and urbanization affect environmental performance. Thirdly, a vital issue in every panel data estimate is the possibility that the individual units of the study have heterogeneity and cross-sectional dependence issues. Incomprehension of cross-sectional dependency might result in inaccurate and inconsistent estimates (Sarkodie and Owusu 2020). To overcome this issue, the current study uses a cross-sectional dependence test and contemporary heterogeneous panel approaches, including the pooled mean group (PMG), dynamic modified ordinary least square (DOLS), fully modified ordinary least square (FMOLS), and Dumitrescu–Hurlin panel causality test. Accordingly, policymakers need to understand the critical role of economic complexity and renewable energy on carbon emissions to take the appropriate actions to mitigate the negative consequences of environmental pollution. In addition, the study's findings suggest environmental policies that encourage investment in renewable energy production and technological and green innovations.

The remainder of the article will be structured as follows. The "Literature review" section exhibits the relevant literature. The data and econometric methods of the study are presented in the "Data and methodology" section. The "Empirical results and discussion" section presents the empirical findings, robustness, and discussion of the results. The last section concludes and present the relevant policy implications drawn from the findings.

Literature review

Recent years have seen an upsurge in studies looking into the elements that mitigate environmental pollution. The literature has considered several factors, including renewable energy consumption, institutional quality, green innovations, economic complexity, and financial development. Even though the empirical studies considered countries with different stages of development, however, there is an absence of harmony in their findings due to discrepancies in the estimation techniques, data, and variables employed. Hence, this section summarizes the relevant literature on economic complexity, renewable energy use, economic growth, urbanization, and carbon emissions.

Economic complexity and environmental pollution

Based on economic complexity, the literature discovered that the emission pattern displays an inverted U-shaped curve (Khan et al. 2022; Neagu 2019; Pata 2021). The evidence presented that pollution rises during the preliminary stages when the complexity of the nation's exports is lower. Environmental quality improves after a certain threshold level because of rising economic complexity, which is associated with technology-intensive products that are environmentally friendly. By applying various panel data analyses, a considerable number of empirics observed that economic complexity might aid in reducing the issues of environmental degradation (Doğan et al. 2019; Leitão et al. 2021; Swart and Brinkmann 2020). Likewise, Boleti et al. (2021) discovered in a panel of 88 nations that when the exported commodities are more sophisticated, the environmental quality improves. Moreover, Can and Gozgor (2017) examined the impacts of energy consumption and economic complexity on CO_2 emissions in France. They found that while energy usage increases environmental deterioration, economic complexity lowers CO_2 emissions over the long run. Ahmed et al. (2022) observed that the economic complexity of G7 countries contributes to improving their environmental quality. Similarly, Sun et al. (2022) confirmed from the method of moment quantile regression (MMQR) that economic complexity significantly impacts reducing emissions, especially at higher emission quantiles. The study further demonstrated that economic complexity promotes switching to renewable energy, significantly lowering carbon emissions. Furthermore, Adedoyin et al. (2021) identified that a rise in economic complexity not only reduces emissions but also moderates the significance of economic growth in the environmental deterioration of Japan.

Even though the evidence that economic complexity improves environmental quality is growing, a portion of the literature concluded the opposite (Kazemzadeh et al. 2022; Neagu 2020). For instance, Rafique et al. (2022) found from the world's top 10 highly sophisticated nations that economic complexity, trade, and urbanization lead to larger ecological footprints. In contrast, human capital and renewable energy production reduce them. Similarly, Adebayo et al. (2022) demonstrated that CO_2 emissions are dramatically increased by energy consumption and economic complexity in MINT countries. The authors observed a unidirectional causality from economic complexity and energy consumption to CO_2 emissions. Similar findings were concluded by Shahzad et al. (2021) in the USA and Yilanci and Pata (2020) in China by both applying the ARDL approach. Additionally, Taghvaee et al. (2022) inspected how different economic sectors affect environmental pollution by considering the economic complexity of OECD economies between 1971 and 2016. They noted that, compared to other economic sectors, the service industry has the most polluting structure, and economic complexity has positively impacted CO_2 emissions.

Some empirical studies discovered that the effect of economic complexity varies with countries' income levels. Depending on panel quantile regression methods, Doğan et al. (2019) examined the relationship between economic complexity and carbon emissions in 55 countries between 1971 and 2014. The findings demonstrate that economic complexity has decreased CO_2 emissions in high-income nations while increasing environmental deterioration in lower and upper middle-income countries. Likewise, Neagu (2019) investigates the long-term relationship between economic complexity, energy consumption structure, and greenhouse gas emission of the most complex and lowest complex economies in Europe. The findings from the heterogeneous panel approach found a more robust relationship for the less complex economies, indicating an increased risk of pollution as economic complexity rises.

Renewable energy consumption and environmental pollution

Researchers have a consensus that renewable energy use is pivotal to achieving a sustainable environment. For instance, Yuping et al. (2021) assessed the dynamic impacts of renewable and non-renewable energy sources, globalization, and economic growth on carbon emission levels in Argentina between 1970 and 2018. The evidence from ARDL estimations demonstrated that the use of renewable energy and globalization decreased emissions, whereas the use of non-renewable energy increased emissions both in the short run and long run. Likewise, Lee (2019) and Wahab et al. (2022) observed that renewable energy consumption negatively and significantly impacts the CO_2 emissions of the European Union and BRICS countries. The evidence that renewable energy use improves environmental quality was asserted by Adedoyin et al. (2021) in Japan and Adebayo et al. (2022) in Portugal. It is noteworthy that renewables improve environmental quality and also contribute to long-run economic growth (Saidi and Omri 2020). Moreover, Azam et al. (2021) presented that developing and improving renewable energy sources is essential to combating climate change and global warming while fostering economic growth in the ten highest carbon dioxide-emitting countries. Besides renewable energy use, many studies have identified that technological and green innovations improve environmental quality (Jian and Afshan 2022; Qin et al. 2021; Sharif et al. 2022; Suki et al. 2022).

A sizable number of empirical studies investigated the effects of renewable energy use on environmental pollution in Africa. For example, Warsame et al. (2022) examined how institutional quality and the use of renewable energy affected environmental deterioration in Somalia from 1990 to 2017. Their long-run ARDL outcomes show that renewable energy and institutional stability improve environmental quality. Using a system generalized method of moment (GMM), Hanif (2018) examines the effects of renewable energy sources on environmental degradation in 34 sub-Saharan African nations between 1995 and 2015. The authors demonstrated that switching to renewable energy enhances air quality by reducing carbon emissions and household exposure to harmful pollutants. Additionally, Attiaoui et al. (2017) applied the PMG estimator to examine the effects of renewable and non-renewable energy consumption and economic growth on CO_2 emissions of 22 African countries from 1990 to 2011. They concluded that carbon emissions are increased by economic growth and non-renewable energy use, whereas renewable energy consumption alleviates environmental degradation.

Economic growth and environmental pollution

Economic growth is perceived to be one of the driving factors of environmental degradation. The Environmental Kuznets Curve (EKC) hypothesis is evaluated to investigate the nexus between income per capita and environmental pollution (Yilanci and Pata 2020). According to the theory, environmental deterioration grows until the economy reaches a high-income level; after that point, technical advancements lead to enhanced environmental quality. Can and Gozgor (2017) validated the hypothesis in France, while Yilanci and Pata (2020) did not support the theory in the case of China. Moreover, Shaheen et al. (2019) examined the relationship between GDP and carbon emissions in Pakistan from 1972 to 2014. They implemented the ARDL technique, which presented that energy consumption and economic growth increase CO_2 emissions in the long run. Correspondingly, Saint Akadiri et al. (2020) explored the relationships between carbon emissions, energy consumption, economic growth, and globalization in Turkey from 1970 to 2014. The long-term statistical drivers of carbon emissions in Turkey are energy consumption and economic growth. Similarly, Sharif et al. (2020) discovered that long-run and short-run economic growth and non-renewable energy use are the driving factors of environmental deterioration in Turkey.

Some recent studies adopted panel data analysis across different regions to outline the economic growth-environmental degradation nexus. For instance, Adebayo et al. (2022) observed that the impact of economic growth on carbon emissions is favorable and is statistically significant in MINT countries. Similarly, Musah et al. (2021) observed that West African countries' economic expansion had a considerably favorable effect on environmental deterioration. Moreover, Kahia et al. (2019) examined the effects of economic growth on carbon dioxide emissions in 12 Middle Eastern and North African countries between 1980 and 2012. The panel vector autoregressive (PVAR) model results demonstrate that environmental deterioration is caused by economic expansion, but using renewable energy reduces it.

Urbanization and environmental pollution

The impacts of urbanization on environmental degradation are higher in countries with lower environmental concerns compared to those with higher awareness. For instance, Wang et al. (2021) investigated the connections between urbanization and three carbon emission characteristics, namely, CO_2 emissions per capita, total CO_2 emissions, and CO_2 emission intensity in OECD high-income countries. They confirmed that urbanization in industrial economies has a negative impact on carbon emissions, while it has an inverted U-shaped effect on carbon emission intensity. In addition, Zhang et al. (2017) observed that urbanization improves environmental quality in OECD nations. Using the ARDL approach, Ali et al. (2017) concluded that urban expansion in Singapore does not pose a barrier to the improvement of environmental quality.

In contrast, the evidence from developing countries reveals that, due to urbanization, environmental quality deteriorates. Musah et al. (2021) examined the connection between urbanization and carbon emissions in West African countries. According to the findings, urbanization considerably increased CO_2 emissions. In addition, Wu et al. (2016) also discovered that a higher urbanization rate escalates carbon emissions in urban and rural Chinese areas. Notwithstanding, Khan and Su (2021) found that urbanization of the newly industrialized nations positively impacts carbon dioxide emissions when below the threshold value. Moreover, Wang et al. (2016) examined the relationship between urbanization, energy consumption, and carbon emissions in ASEAN nations from 1980 to 2009. The results from panel cointegration analysis confirm that an increase in urban population causes a spike in carbon emissions. Sun et al. (2018) and Sun and Huang (2020) examined the relationship between carbon emissions and urbanization across Chinese provinces. They concluded that urbanization intensifies environmental pollution.

The literature thoroughly emphasized the importance of economic complexity and renewables for sustainable development. However, the studies that investigate the connection in SSA still need to be included. Therefore, this study aims to examine the role of a country's economic structures and renewable energy consumption on environmental performance in SSA countries. To achieve this objective, the study uses a heterogenous panel approaches to account for cross-sectional dependence and heterogeneity issues in panel data analysis.

Data and methodology

Data

The study employs annual panel data to investigate the effects of renewable energy consumption, economic complexity, economic growth, and urbanization on carbon emissions in sub-Saharan Africa from 1999 to 2018. The data were gathered from the world development indicators (WDI) and the observatory of economic complexity (OEC). The study adopts carbon dioxide emission to measure environmental pollution, economic complexity and renewable energy consumption, economic growth, and urbanization. Table 1 exhibits each variable's symbol, measurement, and data sources. Also, Fig. 1 shows a visual representation of the analysis flow.

Econometric model

The model specifications of the present study follow the model specifications of Adedoyin et al. (2021), Doğan et al. (2021), Rafique et al. (2022), and Saidi and Omri (2020). As a result, the below panel data model was utilized to examine the impacts of renewable energy use, economic complexity, economic growth, and urbanization on environmental pollution in SSA nations.

$$CO_2 = f(\mathrm{REC}, \mathrm{ECI}, \mathrm{GDP}, \mathrm{URB}) \tag{1}$$

where CO_2 denotes carbon emissions, which is the dependent variable, REC represents renewable energy consumption, ECI signifies the economic complexity index, GDP indicates the real gross domestic product, and URB stands for urbanization. To lessen the heterogeneity problems that typically arise in heterogeneous panel data and ensure that the variables are interpreted as percentages, the examined variables were turned into a natural logarithm, except for economic complexity. The modified form is as follows:

$$\ln CO_{2_{it}} = \beta_0 + \beta_1 \ln \mathrm{REC}_{it} + \beta_2 \mathrm{ECI}_{it} + \beta_3 \ln \mathrm{GDP}_{it} + \beta_4 \ln \mathrm{URB}_{it} + \varepsilon_{it} \tag{2}$$

Based on the panel dataset with a number of individual units, $i = 1, 2, 3, \ldots, N$ and the number of observations $t = 1, 2, 3, \ldots, T$. β_0 is the intercept, β_1, and β_2 are the coefficients of renewable energy consumption and economic complexity, which are expected to have a negative impact on environmental pollution. However, β_3 and β_4 are the coefficients of economic growth and urbanization, which are expected to have positive effect on carbon emissions. The ln signifies the natural logarithm, and ε signifies the white noise error term.

Econometric approach

Cross-sectional dependence

The prospect that the individual units are interdependent is a significant issue that inevitably emerges in every panel data estimate, which has possible repercussions to parameter estimates and inference. This interrelatedness arises from globally common shocks or regional spillovers with heterogenous effects across countries. The ignorance of cross-sectional dependence might lead to invalid and inconsistent estimates (Sarkodie and Owusu 2020). Due to the nature of the interdependence between SSA nations in terms of trade, geography, and culture, a conceivable cross-sectional reliance exists across countries. Thus, the initial step is to inspect the cross-sectional dependence among the examined panels. One of the most frequent tests is the Lagrange multiplier (LM) statistic by Breusch and Pagan (1980). The null hypothesis of cross-sectional independence$H_0 : \hat{\rho}_{ij} = \hat{\rho}_{ji} = \mathrm{cor}\left(\hat{u}_{it}, \hat{u}_{jt}\right) = 0, i \neq j$, which states that the link between the disturbances in distinct cross-sections is zero, against the alternative hypothesis of cross-sectional dependence, that implies the correlation is different from zero $\left(H_1 : \hat{\rho}_{ij} = \hat{\rho}_{ji} \neq 0, \mathrm{for some} i \neq j\right)$. Pesaran (2004)

Table 1 Symbols, measurement, and sources of variables

Variable	Symbol	Measurement	Source
Dependent variable			
Environmental pollution	CO_2	Metric tons per capita	WDI
Independent variables			
Renewable energy consumption	REC	% of total final energy consumption	WDI
Economic complexity	ECI	The index of economic complexity	OEC
Control variables			
Economic growth	GDP	GDP constant 2015 US$	WDI
Urbanization	URB	Urban population (% of the total population)	WDI

Fig. 1 The flow of the analysis

introduced a straightforward alternative test with a mean precisely equal to zero and based on regular product-moment correlation coefficients for constant values of either N or T. In the event of balanced panel data, the CD statistic of Pesaran might be calculated as follows:

$$\mathrm{CD} = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \overset{d}{\rightarrow} N(0,1) \tag{3}$$

Slope heterogeneity test

In analyzing panel data, it is crucial to determine whether the slope coefficients are homogenous. Lack of consideration to investigate the homogeneity of the data might lead to unobserved country-specific attributes (Bedir and Yilmaz 2016). Most of the studies implement Pesaran and Yamagata (2008) test to determine whether the slope coefficients were heterogeneous. The following standardized dispersion statistic is used for testing homogeneity:

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S} - k}{\sqrt{2K}}\right) \tag{4}$$

where k is the number of explanatory variables and $\tilde{S}$ stands for the modified Swamy test. The $\tilde{\Delta}$ test has an asymptotic standard normal distribution when the error terms are normally distributed under the null hypothesis with the constraint of $(N, T) \rightarrow \infty$. Small samples are handled using the following adjusted $\tilde{\Delta}$ test:

$$\widetilde{\Delta}_{\text{adj}} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S} - E\left(\widetilde{Z}_{iT}\right)}{\sqrt{\text{Var}\left(\widetilde{Z}_{iT}\right)}}\right) \tag{5}$$

where $E\left(\widetilde{Z}_{iT}\right) = k$, and $\text{Var}\left(\widetilde{Z}_{iT}\right) = 2k(T-k-1)/(T+1)$. The null hypothesis of the test is that all slopes are homogenous, which suggests that every slope coefficient is constant for all cross-sectional units.

Panel non-stationarity test

When cross-sectional dependence exists, the first-generation panel unit root tests that assume cross-sectional independence might result in inaccurate estimates (Breitung and Das 2008). Therefore, to ensure the accuracy and reliability of the outcome given the interdependence of individual panel units, Pesaran (2007) suggested second-generation panel unit root tests such as the cross-sectional ADF (CADF) and the augmented cross-sectional IPS (CIPS). These tests consider the possibility of cross-sectional dependence resulting from unobserved common factors. Pesaran (2007) presented that the initial estimates of the CIPS test are made using the CADF model. CIPS statistic is calculated as follows using the CADF statistic values for each cross-section unit:

$$\text{CIPS} = \frac{1}{N}\sum_{i=1}^{N}\text{CADF} \tag{6}$$

Panel cointegration analysis

Prior to the long-run estimation of the variables, it is necessary to investigate the presence of a cointegration relationship between them. Pedroni (1999, 2004) is the most frequent method adopted in the literature. Unlike other cointegration tests, the Pedroni test allows for panel-specific fixed effects and panel-specific time trends in the cointegrating regression model, where the AR coefficient varies across panels. The null hypothesis of no cointegration is tested against the alternative hypothesis, which indicates the existence of cointegration among the variables of interest. Moreover, Westerlund (2005) proposed a panel cointegration test, which addresses the CD problem and determines if the linear combination of the series is stationary or exhibits a cointegration connection. Westerlund constructed a set of variance ratio (VR) test statistics for the null hypothesis of no cointegration, and the alternative hypothesis indicates that the series in some of the panels are cointegrated. Hence, the null hypothesis of no cointegration association would be rejected if the p-value is significant at 1%, 5%, and 10%, respectively.

Panel autoregressive distributed lag (ARDL) technique

Pesaran et al. (1999) and Pesaran (2004) developed the mean group (MG) and pooled mean group (PMG) techniques to determine the long-run and short-run estimations. The PMG estimator requires the long-run coefficient vectors to be identical across all country groups, as well as letting group-specific short-run slope coefficients vary across nations. In situations when there is long-run homogeneity, the PMG is a reliable and effective estimator. The PMG method has the advantage of predicting the long-run and short-run parameters regardless of whether the series is integrated at I(0), I(1), or a combination of both. The MG technique, however, is more dependable when the slope and constants vary for each country group. The averages of the N individual group regressions are used to fit the parameters of this model. Hausman (1978) establishes the null hypothesis of homogeneity constraint on the long-run coefficients for comparing the PMG and MG estimators. To measure the role of renewable energy use, economic complexity, economic growth, and urbanization on carbon emissions in SSA countries, the study used a panel ARDL technique. According to Pesaran et al. (1999), the study's panel ARDL framework (p, q, q, q, q) is as follows:

$$\begin{aligned}\Delta \ln CO_{2_{it}} &= \alpha_0 + \varphi_1 \ln CO_{2_{it-1}} + \varphi_2 \ln REC_{it-1} + \varphi_3 ECI_{it-1} + \varphi_4 \ln GDP_{it-1} + \varphi_5 \ln URB_{it-1} \\ &+ \sum_{i=1}^{p} \delta_1 \Delta \ln CO_{2_{it}-k} + \sum_{i=1}^{q} \delta_2 \Delta \ln REC_{it-k} + \sum_{i=1}^{q} \delta_3 \Delta ECI_{it-k} + \sum_{i=1}^{q} \delta_4 \Delta \ln GDP_{it-k} \\ &+ \sum_{i=1}^{q} \delta_5 \Delta \ln URB_{it-k} + \mu_i + \varepsilon_t\end{aligned} \tag{7}$$

where α_0 is the intercept, φ is the long-run coefficient, δ indicates the coefficient of short-run variables, p and q represent the number of lags, Δ is the first difference operator, ε_t is the error term, and μ_i captures country-specific effects.

Dumitrescu–Hurlin panel causality test

Dumitrescu and Hurlin (2012) causality test applies the design to test causality test in a heterogenous panel data framework with constant coefficients. According to Lopez and Weber (2017), assume that there may be causality for some cross-sections in the panel but not necessarily for all cross-sections. Therefore, the present study uses the Dumitrescu–Hurlin panel causality test to demonstrate whether renewable energy consumption, economic complexity, economic growth, urbanization, and carbon emissions are causally related. The fact that Dumitrescu–Hurlin panel causality holds for heterogeneous panels, regardless of whether $N > T$ or $N < T$, is remarkable. The fundamental regressions for X_{it} and Y_{it} are

$$Y_{i,t} = a_{1i} + \sum_{k=1}^{K} \beta_{ik} X_{i,t-k} + \sum_{j=1}^{K} \gamma_{ik} Y_{i,t-k} + u_{1i,t} \tag{8}$$

$$X_{i,t} = a_{2i} + \sum_{k=1}^{K} \theta_{ik} X_{i,t-k} + \sum_{k=1}^{K} \delta_{ik} Y_{i,t-k} + u_{2i,t} \tag{9}$$

The notations $X_{i,t}$ and $Y_{i,t}$ denote the values of two stationary variables for cross-section i in the period t. The coefficients are permitted to vary between cross-sections, although they are presumed to be time-invariant. The panel must be balanced, and the lag order K is expected to be the same for all N cross-sections. Moreover, the null and alternative hypothesis for evaluating the Dumitrescu–Hurlin panel causality is expressed as follows:

$$\begin{aligned} H_0 &: \delta_i = 0 \forall_i = 1, \ldots, N \\ H_1 &: \delta_i = 0 \forall_i = 1, \ldots, N \\ H_1 &: \delta_i \neq 0 \forall_i = N+1, N+2, \ldots, N \end{aligned} \tag{10}$$

The null hypothesis of the test indicates that there is no homogenous causality among the whole cross-sections, while the alternative hypothesis confirms that there is evidence of at least one causal relationship in the panel data.

Empirical results and discussion

Descriptive statistics and correlation analysis

Table 2 contains the descriptive statistics and correlation analysis of the variables. Panel A of the analysis demonstrates the mean, volatility, maximum and minimum values, and skewness of the data. The ECI has the lowest average value at − 0.831 and the highest standard deviation of 0.636, whereas its maximum and minimum values are 0.749 and − 2.786, respectively. This indicates that the SSA countries are poorly diversified, although their complexity levels have improved recently. The evidence further presents that urbanization and renewable energy consumption are the least volatile. Carbon emissions have a mean of − 0.551 and the lowest maximum value of 0.933. Moreover, the mean, maximum, and minimum GDP values are the highest throughout the sample. Besides, the analysis indicates that renewable energy use, economic complexity, and urbanization are negatively skewed, whereas carbon emissions and economic growth are positively skewed. The evidence from the Jarque–Bera test exhibits that all variables are distributed normally at the 1% significance level, except ECI. On the other hand, panel B of Table 2 shows the correlation among the variables to make sure that there is no multicollinearity. Notwithstanding, environmental pollution is negatively correlated with renewable energy consumption while it relates positively to economic growth, urbanization, and economic complexity. Urbanization is positively associated with carbon emissions and economic growth, although it is correlated negatively to renewable energy use and economic complexity.

Table 2 Descriptive statistics and correlations analysis

Panel A: descriptive statistics summary					
	$\ln CO_2$	lnREC	ECI	lnGDP	lnURB
Mean	− 0.551	1.818	− 0.831	10.005	1.533
Std. dev	0.570	0.208	0.636	0.583	0.197
Maximum	0.933	1.993	0.749	11.692	1.951
Minimum	− 1.787	0.964	− 2.786	8.818	0.905
Skewness	0.416	− 2.238	− 0.069	0.493	− 0.574
Kurtosis	2.623	7.992	2.681	3.268	3.048
Jarque–Bera	28.401***	1532.402***	4.114	35.626***	45.022***
Panel B: pairwise correlations					
$\ln CO_2$	1				
lnREC	− 0.748	1			
ECI	0.014	− 0.282	1		
lnGDP	0.363	− 0.232	− 0.208	1	
lnURB	0.618	− 0.396	− 0.193	0.213	1

*** indicates statistical significance at the 1% percent level

Table 3 Test of cross-sectional dependency

H_0: no cross-section dependence

Variable	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
$\ln CO_2$	5784.783	122.597	121.518	32.382
	[0.000]	[0.000]	[0.000]	[0.000]
lnREC	5805.728	123.114	122.035	42.075
	[0.000]	[0.000]	[0.000]	[0.000]
ECI	2939.438	52.336	51.257	0.296
	[0.000]	[0.000]	[0.000]	[0.767]
lnGDP	13,574.61	314.953	313.874	112.59
	[0.000]	[0.000]	[0.000]	[0.000]
lnURB	14,461.15	336.844	335.765	96.934
	[0.000]	[0.000]	[0.000]	[0.000]

Table 4 Results of slope heterogeneity

H_0: coefficient slopes are homogeneous

	Statistic	*p*-value
$\tilde{\Delta}$	23.865	0.000
$\tilde{\Delta}$ Adjusted	28.584	0.000

Table 5 Panel unit root test outcomes

	CIPS		CADF	
	Level	1st difference	Level	1st difference
$\ln CO_2$	−2.489***	−4.270***	−1.514	−2.168***
lnREC	−2.420***	−4.013***	−2.082**	−1.991*
ECI	−1.797	−3.833***	−1.771	−2.112***
lnGDP	−1.709	−3.488***	−1.713	−2.012**
lnURB	−2.214**	−1.435	−1.116	3.855***

Cross-sectional dependence and slope heterogeneity test

The earlier step is to examine the cross-sectional dependence among the panels via the following tests: Breusch and Pagan (1980) LM test, bias-corrected LM test, Pesaran (2004) scaled LM, and Pesaran (2015) CD test. Table 3 reports the outcomes of the cross-sectional dependence analysis based on these tests. The null hypothesis of no cross-section dependence was rejected at the 1% significance level for all series, which provides strong evidence of cross-sectional dependence among the countries.

Furthermore, Pesaran and Yamagata (2008) were used to assess the homogeneity of the slope coefficients. The test results shown in Table 4 indicate that the null hypothesis of homogenous slope coefficients was rejected based on the statistical values of delta-tilde and delta-tilde adjusted as well as their *p*-values. The results imply heterogeneity in the slope coefficients across various cross-sections. This shows that using heterogeneous panel estimators is suitable for our research.

Panel unit root test results

Subsequently, after finding strong evidence of cross-sectional dependence and slope heterogeneity, the study adopted second-generation panel unit root tests appropriate for heterogenous panel estimates with correlation across cross-sections. The study conducted CIPS and CADF tests to determine the order of integration of the series. The null hypothesis of the tests indicates that the data is non-stationary against the alternative hypothesis that suggests at least one of the cross-sections is stationary. Table 5 presents the results of the panel unit root test. The unit root test results reveal that the null hypothesis could not be rejected for most of the series of CIPS and CADF at *I*(0). We further applied the unit root test in the *I*(1) where the null hypothesis was rejected at 1%, 5%, and 10% significance levels for all the series of CADF. However, all series are stationary at *I*(1) for CIPS, except urbanization which is stationary at *I*(0). This order of integration has backed the implementation of the panel ARDL technique in estimating the long-run relationship between the study variables. These findings imply that the underlying variables are integrated into various orders, allowing us to carry out the cointegration test to estimate long-term relationships.

Panel cointegration test

Pedroni and Westerlund tests were adopted to investigate the cointegration relationship among the variables. The results of the cointegration are presented in Table 6. The results of the Pedroni panel cointegration demonstrate that the series are cointegrated for every panel since the probability value of the modified PP, PP, and ADF statistics is less than 1%

Table 6 Panel cointegration tests

	Statistic	*p*-value
Pedroni cointegration test		
Modified Phillips-Perron *t*	4.424	0.000
Phillips-Perron *t*	− 3.9647	0.000
Augmented Dickey-Fuller *t*	− 3.4449	0.0003
Westerlund cointegration test		
Variance ratio	− 2.2867	0.0111

Table 7 Results from the PMG estimator

	PMG		MG	
Variables	Coef	Std. err	Coef	Std. err
Long-run coefficients				
lnREC	− 1.194***	0.059	− 1.757***	0.495
ECI	− 0.076***	0.012	− 0.015	0.025
lnGDP	0.091***	0.028	0.676*	0.392
lnURB	0.406***	0.146	− 2.461	2.178
Short-run coefficients				
ECT$_{-1}$	− 0.154***	0.037	− 0.580***	0.055
ΔlnREC	− 3.210***	0.591	− 2.213***	0.529
ΔECI	0.019**	0.007	0.019*	0.011
ΔlnGDP	0.407***	0.144	0.262*	0.143
ΔlnURB	0.443	1.775	− 10.992	15.640
No. of observations	770			
No. of country groups	41			
No. of years	20			
Hausman chi^2	2.24	*p*-value	0.691	

significant level. Moreover, the findings of the Westerlund cointegration approach indicate that the VR statistics are less than the 1% significance level. The overall results imply that we reject the null hypothesis of no cointegration between renewable energy consumption, economic complexity, economic growth, urbanization, and carbon emissions in favor of the alternative hypothesis that at least some panels are cointegrated.

Long-run and short-run estimates

To proceed to the main estimation, it is a prerequisite to determine whether to apply MG or PMG by using Hausman test. The null hypothesis of the Hausman test is that MG is inefficient against the alternative of PMG is consistent. The results of the Hausman test are presented in Table 7. The chi-square is 2.24 with a *p*-value of 0.691, which suggests that we fail to reject the null hypothesis of homogeneity and allow heterogenous short-run dynamics in the model with a common long-run impact. This implies that the PMG estimator is more convenient for our study. The long-run and short-run estimates of renewable energy consumption, economic complexity, economic growth, and urbanization on carbon emission in SSA countries are presented in Table 7 by applying the PMG estimator. The estimated panel ARDL model is (1, 1, 1, 1, 1) based on AIC.

According to the findings, renewable energy consumption reduces environmental pollution in the long run. A percentage increase in lnREC leads to a 1.194% decline in lnCO$_2$, which is significant at the 1% significance level. Moreover, an improvement in the economic complexity hampers carbon emissions of the SSA countries in the long run. A percentage increase in ECI shrinks lnCO$_2$ by 0.076%, which is significant at the 1% scale. On the other hand, the evidence shows that economic growth intensifies environmental pollution in the long run. A percentage increase in lnGDP leads to a 0.091% increase in lnCO$_2$, which is significant at the 1% significance level. This confirms the direct link between national output growth and environmental pollution. Furthermore, the analysis also presents that expansion in urban population intensifies environmental pollution in the long run. A percentage increase in lnURB increases lnCO$_2$ by 0.406 percentage, which is significant at the 1% threshold. This implies that urbanization amplifies carbon emissions of the SSA countries.

The short-run estimates demonstrate that all control variables influence environmental pollution except urbanization, which was insignificant. Renewable energy use was found to alleviate environmental pollution in the short run. The findings show that a percentage change in lnREC reduces lnCO$_2$ by 3.21%, which is significant at the 1% significance level. This proposes that renewable energy is crucial in reducing the carbon emissions of SSA nations. However, the evidence indicates that economic complexity elevates carbon emissions in the short run. A percentage change in ECI increases lnCO$_2$ by 0.019%, which is significant at the 5% threshold. This implies that economic complexity increases carbon emissions due to the transformation of the economic structures from the reliance on the primary sector to basic manufacturing activities. Additionally, the short-run analysis discovers that economic growth increases carbon emissions in the short run. A percentage change in lnGDP induces lnCO$_2$ to grow by 0.407%, implying that a rise in the national output affects the environment adversely. The degree of adjustment to the long-run equilibrium, ECT, is negative and statistically significant in the short-run estimations, which indicates that any short-run deviation that occurs in carbon emission will be adjusted by the explanatory variables by about 0.154 percent annually.

Numerous empirics from various countries support the study's findings that renewable energy use alleviates carbon emissions. For instance, Warsame et al. (2022) confirmed similar results in Somalia, Yuping et al. (2021) in Argentina, Adedoyin et al. (2021) in Japan, and Adebayo et al.

(2022) in Portugal. Other studies, such as Lee (2019), Saidi and Omri (2020), and Azam et al. (2021), used panel data and concluded that renewable energy consumption improves environmental quality. However, Zaidi et al. (2018) found that using renewable energy did not significantly minimize environmental pollution. It is momentous that Africa is home to the largest sources of renewable energy in the world (Attiaoui et al. 2017). The possibility for sufficient solar radiation throughout the year and the potential for extensive wind energy use exist in SSA countries. Regrettably, the amount of these resources utilized is minimal. This can be attributed to a lack of skilled labor, physical capital, and enough investments in cleaner energy technologies. Technological and green innovations could be a viable way to enhance environmental quality (Qin et al. 2021; Sharif et al. 2022). Additionally, Neagu (2020) suggests that to overcome the increasing non-renewable energy consumption, attention should be given to widespread investment in greener technologies, investments in research and development activities, and the implementation of new energy technologies, including smart grids, carbon capture, storage, and use.

The results of the study that economic complexity enhances environmental quality are comparable to numerous studies in the literature, for example, Doğan et al. (2021) in OECD countries, Leitão et al. (2021) and Sun et al. (2022) in BRICS, Can and Gozgor (2017) in France, and Swart and Brinkmann (2020) in Brazil. In contrast, some other studies observed that economic complexity intensifies environmental pollution, including Rafique et al. (2022) from the top 10 highly complex nations, Adebayo et al. (2022) in the MINT countries, Neagu (2020) from 48 most complex economies, Shahzad et al. (2021) in the USA, and Yilanci and Pata (2020) in China. Technological advancement is perceived to contribute to the mitigation of environmental degradation. The increase in innovation and the diversification of production could make it possible to create new knowledge-intensive products and contribute to greater environmental quality. Some of the fastest-growing developing countries in SSA have transformed their productive capabilities to move from dependence on the agriculture sector towards less complex manufacturing goods. As the complexity of these economies grows, they might move to the use of energy-efficient technologies which improve environmental quality.

The empirical findings also indicate that economic growth contributes to long-run environmental pollution. This finding is comparable to the previous findings of Shaheen et al. (2019) in Pakistan, Saint Akadiri et al. (2020) in Turkey, Adebayo et al. (2022) in MINT countries, and Musah et al. (2021) in West African countries. On the contrary, the results of Can and Gozgor (2017) conclude the existence of a U-shaped relationship between economic growth and environmental deterioration. Moreover, the findings also indicate that urbanization amplifies the environmental degradation of SSA in the long run. This result is supported by many studies conducted in developing countries, such as Musah et al. (2021) in West African countries, Khan and Su (2021) in newly industrialized economies, and Wang et al. (2016) in ASEAN countries. Similarly, several studies observed the evidence from various provinces in China (Sun et al. 2018; Sun and Huang 2020; Wu et al. 2016). On the other hand, the evidence from OECD high-income nations indicates that urbanization negatively influences environmental pollution (Wang et al. 2021; Zhang et al. 2017). Likewise, Ali et al. (2017) found that urban augmentation enhances environmental quality in Singapore.

Sensitivity analysis

The study adopted several cointegration approaches to verify the long-run estimates of the PMG estimator. FMOLS and DOLS have been implemented, as demonstrated in Table 8. The results validate the long-run influences of renewable energy consumption, economic complexity, economic growth, and urbanization on carbon emissions in SSA economies obtained using the PMG estimator. The coefficient signs and significance of the FMOLS and DOLS approaches are consistent with the long-run estimates of the study. This demonstrates that the PMG findings are reliable for policy-making purposes. In addition, the long-run results of the study are presented in Fig. 2.

Dumitrescu–Hurlin causality test

Eventually, the study implemented Dumitrescu and Hurlin (2012) to inspect the direction of the causal relationship between the variables. Table 9 summarizes the outcomes of the causality test. The null hypothesis that lnREC does not homogeneously cause $\ln CO_2$ cannot be rejected. However, evidence refutes the null hypothesis that $\ln CO_2$ does not homogenously cause lnREC at the 1% significance level.

Table 8 Sensitivity analysis of the long-run estimates

	DOLS	FMOLS
Variable	Coefficient	Coefficient
lnREC	−1.770***	−1.711***
	(−62.121)	(−9581.017)
ECI	−0.088***	−0.099***
	(−10.086)	(−156.991)
lnGDP	0.110***	0.109***
	(16.602)	(2402.492)
lnURB	0.959***	0.932***
	(35.758)	(223,186.4)
R^2	0.707	0.701
Adjusted R^2	0.706	0.700

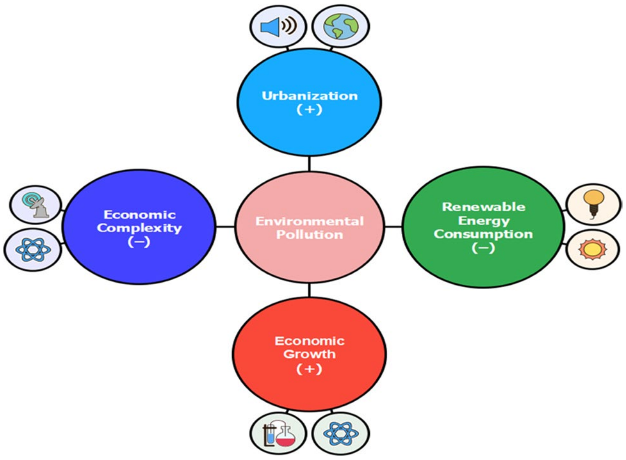

Fig. 2 Graphical presentation of the long-run outcomes

Table 9 Dumitrescu–Hurlin causality test outcomes

Causality path	*W*-stat	*Z*bar-stat	Direction of causality
lnREC → $\ln CO_2$	1.391	0.879	Unidirectional
$\ln CO_2$ → lnREC	3.021***	6.650	
ECI → $\ln CO_2$	1.980***	2.953	Bidirectional
$\ln CO_2$→ECI	2.086***	3.328	
lnGDP → $\ln CO_2$	3.467***	8.230	Bidirectional
$\ln CO_2$ → lnGDP	2.101***	3.392	
lnURB → $\ln CO_2$	3.824***	9.500	Bidirectional
$\ln CO_2$ → lnURB	4.563***	12.118	

→ denotes that variable “*X*” does not homogenously cause variable “*Y*.” *** represents a 1% significance level

This implies that changes in carbon emissions across SSA countries result in variations in renewable energy consumption. The study suggests rejecting the null hypothesis that shifts in ECI does not homogenously cause $\ln CO_2$ is rejected at the 1% threshold. This implies that an increase or decrease in economic complexity results in a rise or fall in carbon emissions. By the same token, the analysis rejects the null hypothesis that $\ln CO_2$ does not homogenously cause ECI, suggesting that variations in carbon emissions considerably lead to changes in economic complexity. Likewise, the results represent that the null hypothesis that lnGDP does not homogeneously cause $\ln CO_2$ was rejected at the 1% significance level. This proposes that changes in economic growth have a significant impact on patterns of environmental pollution. The evidence also shows the null hypothesis that $\ln CO_2$ does not homogeneously cause lnGDP at the 1% significance level. This implies that a rise or drop in carbon emissions resulted in an expansion or reduction in economic growth. Furthermore, the null hypothesis that lnURB does not homogeneously cause $\ln CO_2$ is rejected at the 1% significance level. Therefore, this can be inferred that a shift in urbanization results in changes in environmental pollution. The evidence suggests that $\ln CO_2$ does not homogeneously cause lnURB hypothesis to be rejected at the 1% threshold. This demonstrates that alterations in carbon emissions influence the changes in urbanization.

Conclusion and policy implications

Mitigation of emissions has emerged as a crucial factor for environmental sustainability in the face of rising climate change issues. Improvement of countries’ economic complexity and the use of clean energy sources were proposed to achieve higher environmental quality and sustainable economic growth. Many countries in SSA shifted their economic structure towards complex manufactured activities with environmental consequences. Therefore, the objective of this study is to explore the impact of economic complexity and renewable energy consumption on carbon emissions in sub-Saharan African nations between 1999 and 2018. The study used a PMG cointegration technique to examine the short- and long-run parameters. The investigations discovered the existence of cross-sectional dependence, and the null hypothesis of the slope coefficients homogeneity has been rejected. Because of this, the research used second-generation unit root tests like CADF and CIPS, which ascertained the order of integration of the variables to be a mixed order of stationarity, i.e., *I*(0) and *I*(1). Besides, Pedroni and Westerlund cointegration tests validated the long-run cointegration association between renewable energy use, economic complexity, economic growth, urbanization, and carbon emissions. Additionally, the study used the Dumitrescu–Hurlin test to identify the direction of the causal relationship between the variables.

The empirical findings of the PMG approach indicate that renewable energy consumption alleviates environmental pollution in the long run and short run, although the magnitude is higher in the short run. In addition, economic complexity improves environmental quality in the long run while it worsens in the short run. This suggests that the transition of countries’ economic structures from the dependence on the agricultural sector to the manufactured sector causes economic complexity to raise carbon emissions in the short run. However, as the country’s complexity increases, developing more energy-efficient technologies will improve the environmental quality in the long run. On the other hand, the analysis reveals that long-run and short-run economic growth contribute adversely to environmental damage. Moreover, the study indicates that urbanization worsens environmental pollution in the long run while its short-run impacts are insignificant. DOLS and FMOLS validated the robustness of the long-run findings of the PMG approach.

Table 10 List of countries and codes

No	Country	ISO code	No	Country	ISO code
1	Angola	AGO	22	Malawi	MWI
2	Benin	BEN	23	Mali	MLI
3	Botswana	BWA	24	Mauritania	MRT
4	Burkina Faso	BFA	25	Mauritius	MUS
5	Burundi	BDI	26	Mozambique	MOZ
6	Cameroon	CMR	27	Namibia	NAM
7	Central African Republic	CAF	28	Niger	NER
8	Chad	TCD	29	Nigeria	NGA
9	Côte d'Ivoire	CIV	30	Republic of the Congo	COG
10	D.R. Congo	COD	31	Rwanda	RWA
11	Eswatini	SWZ	32	Senegal	SEN
12	Ethiopia	ETH	33	Sierra Leone	SLE
13	Gabon	GAB	34	Somalia	SOM
14	Gambia	GMB	35	South Africa	ZAF
15	Ghana	GHA	36	Sudan	SDN
16	Guinea	GIN	37	Tanzania	TZA
17	Guinea-Bissau	GNB	38	Togo	TGO
18	Kenya	KEN	39	Uganda	UGA
19	Lesotho	LSO	40	Zambia	ZMB
20	Liberia	LBR	41	Zimbabwe	ZWE
21	Madagascar	MDG			

In addition, the Dumitrescu–Hurlin panel causality test outcomes indicate a unidirectional causal relationship from carbon emissions to renewable energy consumption. The causality results also indicate that carbon emission has a bidirectional causation with economic complexity, economic growth, and urbanization.

Fossil fuels that adversely affect the environment are the main engine of economic growth in many SSA countries. The exploitation of non-renewable energy sources has led to climate change, one of the challenges to the livelihoods of many people in developing countries. It is crucial to focus on structural change and clean energy production to alleviate the negative consequences of the environment. Hence, several policy recommendations can be suggested from the study's findings. Firstly, the SSA countries should change their economic structure towards investment in knowledge-intensive production to generate complex products. Developing highly sophisticated goods is affiliated with technological innovations that minimize the reliance on non-renewable energy and promote environmental quality. It also promises sustainable economic growth in the long run. Since the countries in SSA are less capable of investing in highly complex products, policymakers of these countries can establish incentives to attract high-tech foreign companies. These investments could reduce environmental pollution through the diversification of countries' exports. Secondly, to maximize their production and mitigate carbon emissions, these countries should shift towards the use of renewables. Due to the fact that SSA is rich in renewable energy sources such as wind, solar, and hydropower, governments should adopt policies that ensure investment in renewable energy infrastructures by subsidizing renewable energy initiatives to achieve clean energy. Third, governments should develop national and international policies to enhance sustainable practices to curb the negative consequences of environmental pollution and achieve sustainable economic growth. Policymakers should enforce environmental regulations on manufacturing firms to safeguard the environment by supporting energy-efficient technologies for their production.

Appendix

Appendix Table 10

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Data availability The datasets used and/or analyzed during the current study are available from the author on reasonable request.

Declarations

Ethics approval This study follows all ethical practices during writing. I declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The author declares no competing interests.

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