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The asymmetric effect of biomass energy use on environmental quality: empirical evidence from the Congo Basin

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Abstract

The growing environmental concerns in recent decades have orientated experts' awareness and interest toward environmentally benign research and practices. Efficient utilization of biomass energy features prominently as a cleaner source of energy, a way of reducing the nefarious environmental impacts, and an integral effort to achieve Sustainable Development Goals. Biomass energy usage varies across spatial locations and needs considerable analysis in order to control its impacts. This study investigates the role of biomass energy use on environmental quality while controlling for growth, natural resource rents, and globalization in the Congo Basin from 1980 to 2018. Second-generation econometric techniques like the Cross-Sectional Augmented Dickey-Fuller, bootstrapped co-integration, panel-corrected standard errors, and other robustness checks are utilized for the analyses. The results of the Cross-Sectional Augmented Dickey-Fuller test and bootstrapped co-integration estimates indicate that units are interdependent and variables are co-integrated paving the way for further estimations. The outcomes of the panel-corrected standard errors suggest that (i) biomass energy use promotes environmental quality while (ii) natural resources rent, economic growth, and globalization exert deteriorating effects on environmental quality; (iii) the Dumitrescu Hurlin causality test indicates that both natural resources rent and globalization indirectly affect environmental quality through economic growth. This study represents one of the few to test the implications of biomass energy use on environmental quality in the Congo Basin, motivated by the novel Kindergarten Rule model, which highlights the effect of endogenous technological development in pollution reduction, and helps companies reduce compliance costs despite rising production. Based on these results, the emission reduction potential of biomass energy usage is recognized in the Congo Basin, holding other variables constant. To maintain its status as the world's leading carbon sink, policymakers across the region could start promoting efficient biomass energy technologies while shifting energy-sourcing policies toward renewable energy production. Additionally, for natural resources rent, policymakers could invest heavily in research and development of biomass energy to improve environmental quality while levying heavy taxes on natural resource extraction. Moreover, given the relationship between sound money, trade freedom, and natural resource rents, institutional quality reforms are needed to regulate pollution from natural resource rent in the Congo Basin. Further research could focus on the qualitative determinants of environmental quality in this region

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or a project-based study by involving multiple actors and disciplines in order to uncover, assess and address the uneven impacts on different social groups or regions as the case may be.

Keywords Biomass energy use · Carbon dioxide emission · Congo Basin · Kindergarten rule model · Panel-corrected standard errors · Environmental quality

1 Introduction

The existential threat to environmental quality has attracted immense global attention because of the observed rising concentration of greenhouse gases causing global warming, interrupting the carbon cycle, and causing climate change. Over the past decades, human activities have generated increasing levels of heat-trapping atmospheric gases never seen before for centuries (Nunez, 2019; Yao et al., 2023). Environmental sustainability scientists claim global temperature has witnessed an increase of 1.9°F since 1880 (Hope, 2020). Fossil fuel burning (coal and natural gas) has been reported to be the key driver of global warming (Abbasi et al., 2023; Chiriluș & Costea, 2023). Thus, a wide range of ecological, physiological, and physical phenomena, including acute weather scenarios (severe heatwaves, droughts, storms, floods) sea level rise, and inhibited plant growth are the resulting effects of global warming and climate change (Alnemer et al., 2023; de la Fuente & Williams, 2023; Yufenyuy & Nguetsop, 2020). These environmental impacts may be reduced by the use of wood wastes and agricultural residues to produce board, binder-less board, and paper (Fahmy & Mobarak, 2013; Fahmy et al., 2017; Mobarak et al., 1982a, 1982b). Moreover, all types of organic wastes could be converted to clean fuels, such as hydrogen, and/or petrochemical substitutes via pyrolysis (Mobarak, 1983). Organic wastes may be also converted chemically—by hydrolysis—to sugars, which may be fermented to give bioethanol (El-Shinnawy et al., 1983; Fahmy et al., 1975, 1982, 2020).

However, the existential threat is significant and scientists claim this will inevitably affect future generations if urgent reversal actions are not taken (Addai et al., 2022; Adebayo et al., 2021; Oyebanji & Kirikkaleli, 2022; Yuping et al., 2021; Zhang et al., 2021). As CO_2 and other undesirable pollutants continue to saturate the air, designing holistic carbon policies could become a crucial challenge to scientists (Abbasi & Choukolaei, 2023). Mindful of this global threat, researchers have embarked on developing sustainable solutions aimed at reducing CO_2 emissions, and addressing supply chain management challenges while considering the multifaceted aspects of sustainability and its underlying trade-offs (Abbasi et al., 2023; Abbasi et al., 2021; Abbasi et al., 2021; Abbasi & Erdebilli, 2023). Some studies have focused on assessing sustainability indicators and their contradictory intentions of enhancing energy productivity while reducing environmental costs (Hamedani et al., 2023), while others have proposed policy measures that can potentially balance energy-related trade-offs such as carbon tax, cap-and-trade and several others (Addai et al.,).

One of the most cited factors in environmental quality debates recently relates to biomass energy consumption. As world energy needs continue to surpass population growth, the reliance on fossil-based energy sources induces some socio-economic, political and environmental policy issues for economies across the globe (Ayad et al., 2023; Fakher et al., 2023; Qin et al., 2021; Ramzan et al., 2023). Based on oil peak theory, the primary issues are centered on the fact that the supply of fossil energy is constrained. Secondly, some experts admit that energy safety can be compromised especially for import-dependent economies as they become vulnerable in the events of price shocks (Brown & Huntington, 2008). This condition could be worsened in the events of global health emergencies like the COVID-19 pandemic (Abbasi et al., 2023; Abbasi et al., 2022a, 2022b) and other environmental hazards. Thirdly, researchers and other experts relate environmental deterioration to global warming emanating from CO_2 coming from numerous fossil resources (Lau et al., 2012; Murshed, 2023; Nejat et al., 2015; Saboori & Sulaiman, 2013). With these concerns, biomass energy sourcing is cited as an alternative energy source among other available alternatives with potential economic and environmental benefits due to its substantial scale, storage potential, employment factor and its ability to save foreign exchange from imports (Creutzig et al., 2014; Jiang et al., 2023a, 2023b; Wang et al., 2023; Xin et al., 2023). Figure 1 depicts the CO_2 reduction potential of biomass energy use amid other environmental quality determinants.

Natural resource extraction such as oil, gas, forest, coal (hard vs. soft) and minerals is one of the factors recently found to determine environmental quality (Chen et al., 2023). Rents received from these non-renewable resources may enable a country's capital stock to be liquidated. In theory, when a country's rents are utilized to satisfy immediate consumption rather than financing new capital to replace the depleted resources, it is misappropriating its future capital stock. Taking into cognizance the beneficial effects of natural resources on economic enhancement, analysts believe, has always been crucial in creating a systematic outline for sustainable development (Bosah et al., 2023). Resource extraction revenues, particularly from nonrenewable sources constitute a reasonably large portion of GDP in some countries, and a significant proportion of these remunerations occur in the form of rent-seeking returns that exceed the opportunity cost of extracting the resources.

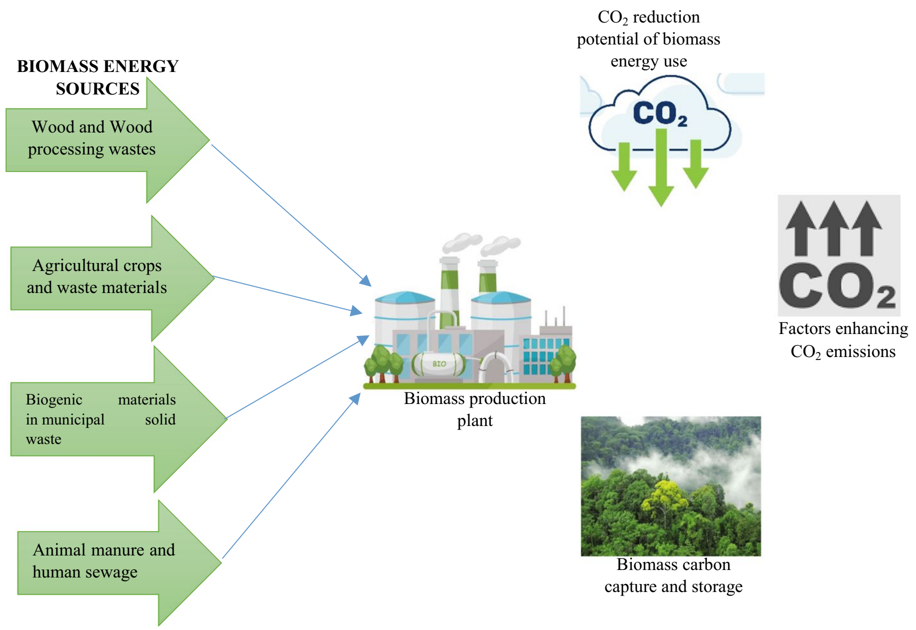

Fig. 1 CO_2 reduction potential of biomass energy use amid other environmental quality determinants. *Source*: Prepared by Authors

Several experts claim that economies that are heavily endowed with natural resources should be more developed than those with little or non-valuable natural resources (Ncube & Koloba, 2020; Umar et al., 2020; Zhao et al., 2020). However, in reality, economies with high natural capital endowments have witnessed an inexplicable degree of poverty, income inequality and political instability than their resource-poor counterparts. Similarly, one of the contentious issues with little consensus hinges on whether natural resource rent can positively or negatively affect the environmental quality of nations.

Given this background, the global quest for sustainable energy policy places these questions to the academia: (i) Can biomass energy consumption be a policy mechanism for sustainable development? (ii) Does any causal link exist between biomass energy use and environmental quality? Can biomass energy consumption affect CO_2 emissions? To answer these sets of questions, the Congo Basin is considered an appropriate geographical space for assessing the asymmetrical effects of biomass energy use on environmental quality. Figure 2 illustrates historical Biomass energy consumption for economies across the Congo Basin enclave.

The Congo Basin is commonly associated with six countries within the region that have massive forest cover: Democratic Republic of the Congo (DRC), Cameroon, the Republic of Congo, Central African Republic, Gabon and Equatorial Guinea as illustrated in Fig. 3. DRC has the most rainforest area of these six countries, with 107 million hectares,

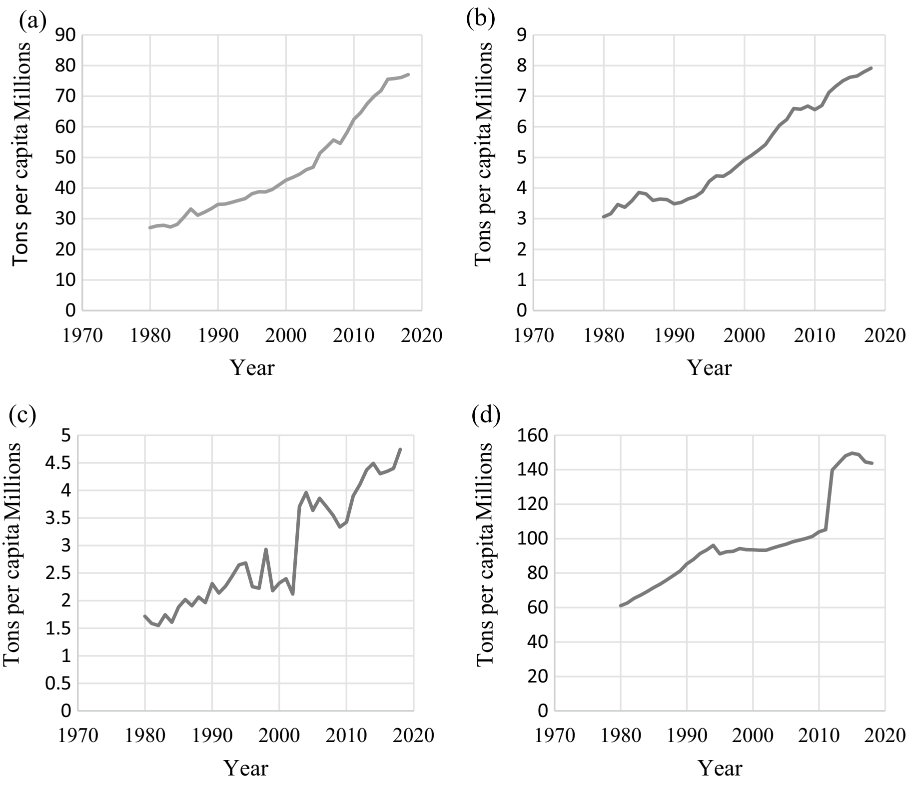

Fig. 2 Biomass energy consumption. Note: (**a–d**) biomass energy consumption for Cameroon, Republic of the Congo, Gabon and The Democratic Republic of Congo, respectively. *Source*: Prepared by authors

Fig. 3 Map of the Congo basin. *Source*: Prepared by authors

accounting for 60% of Central Africa's lowland forest cover (Abernethy et al., 2016). The Congo Basin has a population of more than 75 million (Aquilas et al., 2022). It is home to the second-largest mosaic in the world and has the greatest carbon absorption potential internationally (WB, 2022). However, its carbon repossession capacity is fast fading away owing to the continuous cutting down of forests (Tongele, 2021). It is heavily endowed with almost 178 million hectares (ha) of dense tropical forest (Pinillos, 2021). Despite these rich endowments, the high involvement of Congo Basin countries in foreign trade through the phenomenon of globalization has yielded disproportionate outcomes for its wood processing and inefficient carbonization industries. There are an estimated 44 to 66 million hectares of forest that are covered by the logging industry, according to the Global Forest Atlas. During 2003 and 2018, 54,000 miles of roads for forest concessions were constructed, resulting in 143,500 miles of roads across the enclave, according to a study published in the journal Nature Sustainability in 2019. In May 2002, the World Bank and the Democratic Republic of Congo agreed to a moratorium on logging in the Congo Forest in exchange for a $90 million development aid deal. Sadly, companies pay approximately $18 million in rent annually in concessions.

In the Central African region, the World Wide Fund (WWF) documentation suggests that annual CO_2 emission from deforestation varies from 20 to 60 million tons, while future predictions in the region indicate that by 2050, cutting forest in the Democratic Republic of Congo alone is likely to emit over 30 billion tons of CO_2, which is almost equal to the UK's CO_2 emission over the past six decades.

It is informative to know that for several decades, global partnerships have played a huge role in fostering academic investigation and forest policy design. Even though such supportive engagements have enriched expert understanding of the carbon economy, forest ecology, wildlife spatial distribution, and human role in local forest governance and management from various standpoints, economies in the Congo Basin are yet to have clear-cut forestry policies. Additionally, the Congo Basin is a global ecological hotspot well renowned for its rich biodiversity and researchers have found that it generally harbors taller trees within lower densities of smaller trees as opposed to forests in Latin America (Abernethy et al., 2016). Local populations rely on these forests for livelihood sustenance while the global community considers them as a shield for biodiversity and climate change extenuation. However, countries around the basin do not have clearly defined official forestry policies, mainly because of a lack of research data incorporating CO_2 emissions and its determinants in the Congo basin.

Moreover, the international community has reiterated the need to transition away from the traditional use of biomass as a way to lessen atmospheric GHG emissions. However, bioenergy consumption in the Congo Basin region is predominantly traditional, involving the local use of firewood and charcoal for heating and cooking (Jiang et al., 2023a, 2023b). The recent call by researchers to embrace renewable energy usage is a wake-up call for countries in this enclave to embrace modern bioenergy production and usage.

Given this background rendition, the study reiterates on the lingering questions (i) Can biomass energy consumption serve as a policy framework for sustainable growth in the Congo Basin?; (ii) Is there any causal connection between biomass energy use and environmental quality? (iii) Can biomass energy use affect CO_2 emissions? To give a befitting answer to these questions, we investigated the asymmetric effect of biomass energy use on environmental quality in the Congo Basin from 1980 to 2018, using second-generation-based econometric estimators such as PCSE, Fully Modified Ordinary Least Square (FMOLS), Dynamic Ordinary Least Square (DOLS) and Dumitrescu Hurlin causality assessment tools.

The paper contributes to environmental literature that anticipates strengthening and creating robust balances between biomass usage (SDG 7) and environmental quality (SDG 13). For Congo Basin countries to reduce their greenhouse gas emissions to net zero around 2050 and protect biodiversity, this study contributes to robust policy directions. Additionally, with the current preoccupation with economic growth, economies view environmental action as constraining economic development. To address this challenge, the outcome of the study offers environmentalists, policymakers and economists across the Congo basin, an evidential basis for robust policy action. The study progresses as (i) the next section is the literature review; (ii) the review will be followed by methodology; (iii) section three is empirical outcomes, discussions and limitations (iv) and section four is the conclusion and policy recommendation.

2 Literature review

To help understand the effect of biomass energy use, this review of the previous literature relates to how biomass energy can affect carbon emissions in the Congo basin. To get accurate outcomes from these investigations, the study keeps natural resource rent, economic growth and economic globalization under control since they have historically been validated to contribute to carbon dioxide discussions (Awosusi et al., 2022; Jiang et al., 2023a, 2023b; Wang et al., 2023). This review makes four hypotheses in an attempt to achieve the objectives of this study:

2.1 Hypothesis 1 (H_1): biomass energy consumption promotes environmental quality in the Congo basin

Theoretically, the impacts of biomass use on CO_2 emissions have been explained with varied positions depending on the substitutability of fossil energy under energy pricing theory; land use change factors and crop factors. According to the fossil fuel substitutability theory, since biomass energy can be solid**,** liquid, and, gas, it is easy to store and utilize for many fields, such as heating transportation, and electricity generation (Teske et al., 2011). These factors make fossil sources substitutable with biomass sources, facilitated by its less polluted nature compared to fossil-based energy (Demirbas, 2009). Several studies have indicated that gasoline is replaceable by ethanol energy generated from corn, cellulose and materials from sugarcane (Bilgili et al., 2017; Fontaras et al., 2012; Pradhan & Mbohwa, 2014). In their empirical studies, Pradhan and Mbohwa (2014) found that bioenergy could reduce carbon emissions by 30% in South Africa. Additionally, Fontaras et al. (2012) in their investigations in Greece found that vegetable oil generated fuels has the potential to reduce CO_2 emissions by 30–60%. Similarly, plants and crops participate in the carbon cycle process. Given that plants take in carbon through the soil, plants are included in coal, oil and natural gas production, which makes biomass sourcing akin to fossil energy sourcing in terms of CO_2 emissions generation**.** However, one major role of biomass by nature is to capture CO_2 emissions from escaping into the atmosphere, making biomass energy carbon neutral (Jiang et al., 2023a, 2023b; Repo et al., 2015; Sulaiman & Abdul-Rahim, 2020). Thus, growing energy plants and crops is essential as it helps to reduce net CO_2 by sequestering considerable tons of CO_2 emissions in the soil or preventing them from escaping into the atmosphere (Yao et al., 2023).

Secondly, land use change (whether directly or indirectly occurred) generally culminates in the generation of considerable CO_2 (Fopa et al., 2023; Popp et al., 2012; Xin et al., 2023). This is because producing bioenergy requires a substantial size of land-bearing forest resources, which help trap carbon dioxide emissions. Further, bioenergy production can indirectly increase CO_2 emissions. This is because, the increasing demand for biomass sources leads to increases in agricultural resources for producing bioenergy, causing transformations of forest lands into agricultural lands which can create rises in CO_2 emissions (Piroli et al., 2015). Finally, carbon leakage and green paradox have been used to explain the effect of biomass energy use and CO_2 emissions (Drabik et al., 2010). Several studies indicate that bioenergy policies result in carbon leakages, which cause CO_2 emissions to increase eventually (Drabik et al., 2010; Searchinger et al., 2008). According to carbon leakage paradox, when bioenergy production increases, energy prices fall in the world energy market, inducing increased demand for energy consumption and causing carbon dioxide emissions to rise. When bioenergy production is hugely subsidized, fossil fuel demand falls, causing fossil fuel producers to increase output to breakeven or make some profit in the short term, normally called the Green Paradox (Grafton et al., 2014).

Empirical literature on biomass energy and environmental quality is extensive. Under "Project Feed", Fontaras et al. (2012) modeled/forecasted fuelwood consumption in five European economies (Sweden, Finland, Austria, Portugal and France) between 1995 and 2020 on socioeconomic, environmental, and technical front. The outcomes indicated that fuelwood will moderately lessen the overall GHG emissions in selected economies. However, in Sweden and Finland, there was a projected decrease in carbon emissions. The result was confirmed in a similar study in Sweden by Wahlund et al. (2004). Senatore et al. (2008) established that biodiesel consumption reduces disposable carbon dioxide emissions by 78%. Moreover, Sulaiman and Abdul-Rahim (2020) found that cleaner biomass energy use reduces CO_2 emissions in selected African Countries while Kevser et al. (2022) displayed mixed outcomes regarding the effects of biomass energy consumption on environmental sustainability in 15 selected African countries but suggested that biomass consumption could potentially reduce CO_2 emissions and boost economic growth in the long-term. Other empirical studies which found biomass energy to reduce carbon dioxide emissions include (Khanna et al., 2011; Panwar et al., 2010; Ramzan et al., 2023; Wang et al., 2023). Another study by Suttles et al. (2014) via a global computable general equilibrium model in the European Union and in the US indicate that bioenergy use reduces CO_2 emissions. However, Bento et al. (2015) finds biofuel to cause carbon emissions. Studies by Fangsuwannarak and Triratanasirichai (2013) finds palm diesel oil causes more CO_2 emissions compared to biodiesel fuel.

Empirical studies evaluating the biomass/or carbon absorption potential of the Congo Basin are few with diverse objectives. For instance, Molto et al. (2015) utilized inventory techniques like remote sensing, topography and bioclimatic models to deduce the forest carbon potential of the Congo Basin. Shapiro et al. (2021) developed a metric to quantify estimated changes in aboveground biomass with the aim of tracking the rate of forest degradation across the Congo Basin forest. Their outcome suggests that almost half (20%) of the overall Congo Basin forest is threatened. In line with Shapiro et al. (2021), Migolet et al. (2022) utilized the MARS-based remote sensing approach, with various types of remotely sensed data to evaluate aboveground biomass over the tropical rainforest. A recent study by Jiang et al., (2023a, 2023b) utilized Orbiting Carbon Observatory-2 (OCO-2) satellite observations and a set of physiology-related variables like GPCP precipitation, detrended OCO-2 CO_2 and OCO-2 SIF, to assess the effects of wet/dry seasonal conditions on atmospheric carbon dioxide over the Congo Basin. Their findings indicates that carbon footprint increases by 2ppm in the region owing to biomass burning, especially in the dry season (June July and August) when photosynthetic activities are reduced**.** Based on these findings, their study hypothesize that the status of the Congo Basin could change from global carbon sink to carbon emitter if urgent reversible measures are not taken. Despite the prevailing literature on biomass and environmental quality, no study has focused exclusively on the long run effects of biomass use on environmental quality in the Congo Basin. Additionally, methodological approaches vary across disciplines as we tackled this research problem from an econometric and environmental science perspective. Based on this review, our study assumes that biomass energy consumption promotes environmental quality in the Congo Basin.

2.2 Hypothesis 2 (H_2): natural resources rent leads to declining environmental quality in the Congo basin

Historically, several theories have been propounded to explain factors with fixed economic supply. In economics, theories of the variable economic factor and the marginal productivity have been used to determine with little success, the price of economic factors such as land (fixed) and capital equipment (quasi fixed). However, the theory of rent has been used by recent scholars to describe the fixed factor prices. David Ricardo in his classical rent theory views rent as the cost of using landed resources, thus drawing a clear-cut demarcation from contractual rent which refer to earnings from landlords' invested capital. Thus, rents in this regard denotes the returns set aside by the landlord for land repairs. Secondly, land scarcity has created another dimension of rent. At the national scale, the surface area of land is fixed (or inelastic in nature). Because of variations in the quality of landed properties, the rent paid is called differential rent. In this regard, supplementary amounts paid to an input over its opportunity cost is termed economic rent. Concerning perfectly inelastic or fixed supply of an input, the input price is solely determined by demand and rent in this case refers to every expense made to the input. In the case of a positively sloped or moderately elastic demand curve for an input, rent denotes the portion below the price of an input and the region above the supply curve. No rent is obtained in the case of an elastic supply curve; hence the overall income will be channeled to the occupants (tenants). Nevertheless, contemporary theory do not limit the concept of rent to land, given that rent is applicable to any element or factor which has an inelastic supply in the short term. In economic rent, an entity is paid more than its opportunity cost.

Natural resource rents have been found to play developmental roles, especially in emerging countries. Yet the effects of natural resource extraction processes on the environment remains an issue of concern in recent studies (Ikram et al., 2020). Experts have noted that economic transactions reflected through natural resources rent have played huge roles in the globally rising CO_2 content by 50% in the last few decades. Thus, the pursuit for environmental sustainability should not ignore the role of natural resource rent. The Environmental Kuznets Curve (EKC) features prominently among the key frameworks used in capturing the linkages between resource extraction for economic growth through resource rent and environmental degradation.

According to the EKC framework, there is an initial phase of environmental degradation on the growth path, however this phase improves over time as the economy continues to grow (Grossman & Krueger, 1995). Additionally, the neoclassical theorists claim natural resources exist in abundance and are replaceable by another resource (Torrès & Julien, 2005). Critics however argue, this theory has been used by corporations to contaminate the environment by obtaining emitting permits and licenses (Hediger, 1999). The weak sustainability theories however claim, emitting licenses are means to protect the environment and propel economic activities (Barua & Khataniar, 2016).

Several empirical investigations have validated these theories. For instance, Kwakwa et al. (2020) studied the linkages between natural resources extraction, energy consumption and CO_2 emissions for the case of Ghana from 1971 to 2013 and found natural resources extraction to increase CO_2 emissions. In their studies of sixteen European economies on the relationships between resources rent, renewable energy, non-renewable energy and carbon emissions between 1996 and 2014, Bekun et al. (2019) found that natural resources rent worsens carbon emissions. Other studies that found a positive connection between natural resource rents and CO_2 emissions include (Balsalobre-Lorente et al., 2023; Mesagan

& Vo, 2023; Zhang et al., 2023). Adedoyin et al. (2020) studied the effect of economic growth, coal rent on carbon emissions for BRICS countries between 1990 and 2014. The outcomes indicated an inverse relationship among coal rents, renewable energy output and carbon emissions. A study by Ozturk (2017) to assess the linkages between CO_2 emissions, nuclear and alternative energy use and fossil fuel rents in Latin American economies between 1975 and 2013 indicated a negative nexus between oil rents and CO_2 emissions. On this note, this study hypothesizes that natural resource rents diminish environmental quality.

2.3 Hypothesis 3 (H_3): economic globalization helps to destroy environmental quality at the Congo basin

While different countries use similar terminologies to define globalization, it proxies differ with respect to the empirical analysis and modeling choice. In addition, as trending empirical literature yield diverse findings**,** to better understand the linkages between globalization and environmental quality, several researchers have separated economic from financial globalization. Theoretically, growth is aided by economic globalization through global trade and foreign direct investments (Bilgili et al., 2017). From the EKC framework, the scale effect of economic growth in trade is engineered by globalization with significant environmental quality implications (Gangopadhyay et al., 2023; Kirikkaleli et al., 2021; Ulucak & Ozcan, 2020). This theoretical rendition of environmental impacts of growth in trade lends supports to the pollution haven hypothesis (PHH). This theory claims that purposeful re-allocation of unhealthy industries to economies with less stringent environmental regulations enhances carbon leakages. However, other scholars claim, globalization enables economies to secure funding for investments in clean energy technologies to transform their manufacturing operations that help minimize CO_2 emissions (Alam et al., 2023; Ulucak & Ozcan, 2020). They argue that the negative effects of economic globalization could be avoided by enacting suitable eco-friendly laws and strategies (Sultana et al., 2023; Teng et al., 2021). Several other scholars claim globalization provides superior knowledge and technology transfer to emerging economies toward improving on environmental performance (Nathaniel et al., 2021; Ulucak & Ozcan, 2020). By scaling the arguments above, this study assumes economic globalization reduces environmental quality in the Congo Basin.

2.4 Hypothesis 4 (H_4): rising economic growth has destructive consequences on environmental quality across the Congo basin

Reconciling economic growth and environmental quality continue to remain controversial due to several factors including the advent of novel pollution issues, failure to address the problem of overpopulation in developing economies and the inability to properly handle issues related to global warming. Historically, the limit to growth theory highlight the devastating impacts of uncontrolled growth on the environment, which provides the needed inputs to growth. Additionally, the environment serves as sink for waste depository of economic output. As a sink, economic growth generates undesirable pollutants to various environmental compartments (soil, water, air) or tons of garbage to the environment as repository (AlNemer et al., 2023). The quality of the environment depreciates when the absorption capacity of these compartments is surpassed, thus setting the scene for environmental policy responses to set in for intensive clean up, abatements or to limit growth. In the earliest theoretical expositions regarding energy consumption, economic growth and environmental quality, the EKC literature, has been enormously influential. However, in recent years, while less attention has been given to the definitive extraction of magnesium or oil extraction, it appears more emphasis has been shifted to air quality related issues resulting from industrial activities and global warming. Other theories on economic growth and environmental quality on balanced growth includes (i) Environmental catchup hypothesis; (ii) Green Solow Model by Brock and Taylor (2003) which claims exotic advancement in emission reduction technology lessens emissions and helps to prescribe strict pollution policy; (iii) Stokey Alternative transition paths (Stokey, 1998) on "potential output determination of pollution abatement process" when pollution emissions is considered a factor of production. Some scholars have investigated "growth drag" of natural resource depletion, and find their alignment with limits to growth theory which requires strict environmental policy to guide growth process; (iv) source and sink theory of nature (Pulliam, 1988) which assumes energy consumption draws down available resource stocks and generates emissions that pollute the environment. The theory considers intensity of abatement as constant with no role of technological progress. By this, the economy can reduce emissions from growth through a mix of cleaner production methods based on the (v) Kindergarten Rule model (Brock & Taylor, 2003).

Several empirical studies have equally been conducted to assess the nexus between economic growth and environmental sustainability (Acheampong et al., 2021; Addai et al., 2023a, 2023b; Addai et al., 2022; Adebayo et al., 2021; Jebabli et al., 2023). In an empirical study by Gao and Zhang (2021) the relationship between carbon dioxide emissions and economic output was assessed for 13 Asian economies between 1980 and 2010. They found that carbon emissions has unidirectional causal impact on economic growth with no rebound effect. A study by Ghazouani (2021) in Tunisia between 1972 and 2016 indicated a one-direction causal effect from economic growth to carbon dioxide emissions. In their investigations, Hao et al. (2021) found that economic growth accelerates carbon dioxide emissions in G7 economies**.** This finding was confirmed by Balcilar et al. (2019) for Pakistan from 1971 to 2014; Zhang et al. (2021) in Malaysia; and Minlah and Zhang (2021) in Ghana. However, Zubair et al. (2020) found no causal link between economic growth and carbon emissions in Nigeria. This result was corroborated by Zhang et al. (2020) in their study of 30 provinces in Chinese from 2008 to 2017. Based on this review the study assumes that increasing levels of economic growth has destructive effect on environmental quality in the Congo basin.

Given this extensive literature reviews on the variables of interest, some gaps are evident. While studies incorporating CO_2 emissions have been widely conducted across different regions of the world, such studies are few in tropical African regions. To bring clarity to the inconclusive findings, this paper investigates the asymmetric effect of biomass energy use on environmental quality (CO_2 emissions) at the Congo Basin from 1990 to 2018. Secondly, the impacts of biomass energy use on environmental quality may vary depending its usability and the region of study. Accordingly, Sulaiman and Abdul-Rahim (2020) found that biomass energy use enhances environmental quality in selected African countries whereas Savvakis et al. (2022), Savvakis et al. (2022) disclosed that traditional wood biomass usage increases outdoor and indoor air quality problems in the mountainous Mediterranean area. To supplement existing studies, the Congo Basin presents a suitable case study in tropical Africa to test the implications of biomass energy use on the environmental quality. Third, studies have historically assessed determinants of environmental quality using EKC hypothesis and other growth-related theories. This paper employs the novel Kindergarten Rule model by Brock and Taylor (2003) which complements other growth theories and can highlight the effect of endogenous technological progress in pollution abatement, which help corporations reduce compliance costs despite rising production. Fourth, compared to other empirical investigations carried out in the region, this study utilized second generation-based econometric estimators such as PCSE for long-run assessment, FMOLS and DOLS to ensure the model reports reliable outcomes for policy suggestions.

3 Data and methods

3.1 Data and source

The study seeks to investigate the asymmetric effect of biomass energy consumption on environmental quality in the Congo Basin region from 1980 to 2018. To realize this objective, the study controlled for economic growth, natural resource rent and globalization, which are historically validated factors participating in environmental degradation debates. Data was collected for four Congo Basin countries (Cameroon, the Republic of Congo, Gabon and Democratic Republic of Congo) as depicted in Table 1. (i) Carbon dioxide (CO_2) emission served as a proxy variable for environmental quality and as dependent variable. Carbon dioxide (CO_2) is a gas generated by burning of carbon, and from living organisms as they respire. It is measured in metric tons ($MtCO_2$) (Krey et al., 2014) and it is sourced from OWD (2023). CO_2 emissions is considered a proxy for measuring environmental quality because it is a direct indicator of the amount of pollution that is being released into the atmosphere. Secondly, it is one of the most abundant as well as a major GHG emitted through human activities, and its presence in the atmosphere contributes to climate change. By measuring the amount of CO_2 emissions from a given source, it is possible to determine the level of pollution that is being created. Additionally, CO_2 emissions is relatively easy to measure and can be used to compare the environmental quality of different locations (Tsimisaraka et al., 2023). For determining variables, data were sourced on (ii) GDP per capita (GDP, in constant 2015$), as proxy for economic growth; data was sourced from the WB (2023). Economic growth refers to rise in both quantity and quality of economic goods and services produced and consumed in an economy (Jones & Liu, 2022). GDP per capita is associated with environmental quality because it is related to

Table 1 Data sources. *Source*: Prepared by authors

Code	Description	Unit of measure	Source
LCO_2	Carbon dioxide	CO_2 emissions (tones per capita)	OWD
LGDP	Economic growth	GDP Per Capita (constant 2015 $)	WDI
LBIO	Biomass energy consumption	Biomass energy consumption (tones per capita)	IRP
LNRR	Natural resource Rent	Natural resources rent (% of GDP)	WDI
LGLO	Globalization	Globalization index (economic, social and political aspects)	KOF

Countries considered in this study are Cameroon, the Republic of Congo, Gabon and Democratic Republic of Congo

OWD Our World in Data, *WDI* World Development Indicators, *IRP* International Resource Panel, *KOF* Swiss Economic Institute the level of pollution and resource use. Higher GDP per capita is typically associated with higher levels of pollution and resource use, which can lead to a degradation of environmental quality (Addai et al., 2022). (iii) biomass energy consumption (BIO) was sourced from IRP (2023); Biomass energy is generated from organic materials such as trees, plants, and urban and agricultural waste and has multiple uses including transport fuels, electricity generation and heating (Güney & Kantar, 2020). Typical units of biomass are measured in grams per meter squared (g/m^2), although in other jurisdictions, it is measured in kg/m^2, lb/ft2, etc. and often converted to carbon storage. Biomass energy use is considered a determinant of environmental quality because it is a renewable source of energy and has lower emissions than fossil fuels (Shahzad et al., 2023). (iv) Data on natural resource rent (NRR) was sourced from WB (2023). Total natural resources rents are the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents. Rents realized from mineral extraction or fossil-based extractives and excessive forest resource harvesting renders a country's capital stock bankrupt. Using such rents to satisfy immediate consumption instead of reinvesting it to replace what has been extracted means a country is borrowing against its future needs. On this note, considering the role of natural resource rents to economic performance and environment is key to constructing a robust analytical frame for sustainable development. Earnings from non-renewable resources constitutes a considerably large share of GDP in some countries across the globe and a significant amount of these earnings comes in economic rents with huge opportunity costs (above the cost of extracting the resource). Natural resource rents are computed by differencing the cost of a resource from the mean production cost. This can be realized by subtracting the average cost per unit of harvesting or extracting the resource from the price per unit of the resource. This type of economic activity can have a significant impact on the environment, and so is a determinant of environmental quality (Raihan, 2023). (v) Globalization (GLO) data was sourced from KOF (2023). Globalization is a term used to describe growing interdependence of global economies through cross-border trade, technology, investment flows, migration and information (Gancia et al., 2022). Globalization is measured based on the number of embassies, membership of international organizations, involvement in UN Security Council missions, and number of international treaties signed. It also includes indicators on capital movements and foreign direct investments, international trade, the economic activity of multinational organizations and the internationalization of technology. Moreover, Globalization can lead to increased pollution and resource use, as it can also create incentives for countries to reduce their environmental impacts (Ehigiamusoe et al., 2023). The data series are transformed into their natural logarithm forms to ensure conformity with normal distribution (Addai et al., ; Addai & Kirikkaleli, 2023) before performing the estimations with the aid of Stata version 15 and Eviews version 10 data analysis software. Figure 4 describes the methodological flowchart.

3.2 Framework adoption and model specification

The role of biomass energy, natural resources rent, globalization, economic growth and environmental quality has been a major policy issue for decades (Majeed et al., 2022). Theoretically, economic globalization generates funding for renting natural resources for industrial development. Industrial activity depends immensely on either fossil fuel or bioenergy for continuous production. Policy action is needed to deal with possible environmentally destructive outcomes (Edmonds & Reilly, 1983). Energy consumption supports economic growth to improve living standards and satisfy society's necessities.

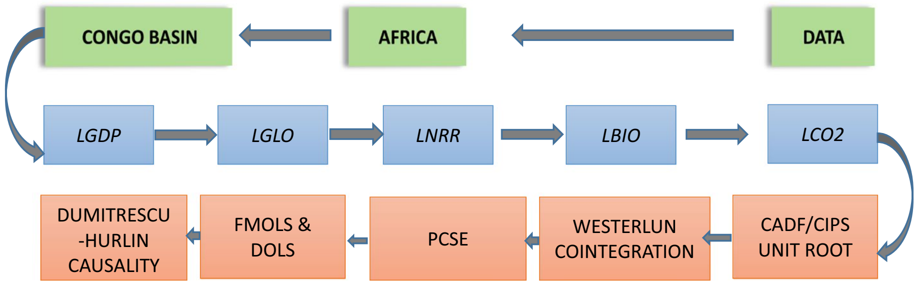

Fig. 4 Methodological flowchart. *Source*: Prepared by authors

However, the energy production mechanism matters for global policy decision-making and environmental quality. To contribute to literature and policy, unlike other theoretical frames, this study adopts the Kindergarten Rule model (Brock & Taylor, 2003) which complements other growth-related theories and highlights the moderating effects of technological advancement on pollution abatement. There are two contributions to discussions provided by the kindergarten model. At the initial point, it demonstrates how technological advancements in abatement can reduce compliance costs in spite of continued growth. As opposed to the Green Solow model, there are ongoing growth drag costs associated with regulation. If abatement is productive, sustainable growth can be achieved without skyrocketing compliance costs. By emphasizing the importance of progress in reducing emissions, this model emphasizes the importance of making the direction and rate of technological progress endogenous. Second, the model generates an initial worsening environmental situation very similar to that of the Stokey (1998) model and the EKC hypothesis espoused by Grossman and Krueger (1995). The nexus between income and pollution varies systematically across economies, as explained by this framework (Addai et al., 2023a, 2023b).

The catastrophic regime ecosystem by-products of all production is modeled by an algebra that describes pollutant emission as a measure of economic activities, its composition and the purity of the production methods utilized as expressed in Eq. (1).

$$E = \sum_{I=1}^{n} a_i s_i Y \text{ where } \sum_{I=1}^{n} s_i = 1 \tag{1}$$

where E denotes the overall production-based pollution in a country, n represents manufacturing, a_i output per dollar emissions arising from manufacturing $_i$; s_i denotes the value share of industry $_i$ in nationwide production; and Y denotes total nationwide production. By differentiating both sides regarding time, the model becomes

$$E = \sum_{i=1}^{n} \pi_i \left[\hat{a}_i + \hat{s}_i\right] + Y, \text{ where } \pi = \frac{E_i}{E} \tag{2}$$

where $\hat{a}$ over x designates $[\mathrm{d}x = \mathrm{d}t]/x$. Variations in total emissions can emanate from three sources denoted to be the scale, composition and technology effects.

By modeling the environment as a conducive ground for disposing human waste, it is assumes that naturally regenerated emissions can be used to measure environmental quality. This means, by adjusting the environment to changes in levels of pollution, natural regeneration could determine environmental quality. Here, since emissions over time is E, the pollution stock evolution is given by

$$X = E - \eta X \text{ where } \eta > 0 \tag{3}$$

where X is assumed to be a confined milieu for human existence, and a simple adverse linear association between the stable state generation of pollution E, and the pollution stock X.

Since energy is demanded in all works, it is constantly and unintentionally used up in the production process, thus generating pollution assumed as

$$i, t \geq 0, \lim\inf\,[a, (t)] > 0 \tag{4}$$

Implying that for each $_{\mathrm{i}}$, a strictly positive ">0 such that $a_i(t)$>". It also implies that the transient to emission reduction happens at the composition effects phase as

$$E(t) \leq B \Rightarrow \sum_{t=1}^{n} a, [t]s, [t] \leq \frac{B}{Y[t]} \text{ for all } t \geq 0 \tag{5}$$

However, if the world is to emit with growing $Y(t)$, uncontaminated manufacturing rate should be attained at $a_i\,(t)$ trending toward nil. Consequently, achieving zero emissions and economic growth simultaneously is potentially doable if emission benign technologies are promoted, leading to reductions in emissions per unit output as denoted by

$$\overset{*}{a}(t) := (a, [t]) \leq \frac{B}{Y[t]} \rightarrow 0 \text{ as } t \rightarrow \infty. \tag{6}$$

Based on this theoretical background this study models the asymmetrical effects of biomass energy use, natural resource rent, globalization and economic growth on environmental quality in the Congo Basin as

$$\mathrm{CO}_{2t} = \mathrm{BIO}_{it},\ \mathrm{NRR}_{it},\ \mathrm{GLO}_{it},\ \mathrm{GDP}_{it},\ \mathrm{e}_{it} \tag{7}$$

$$Y = f\left(X_{1it}, X_{2it}, X_{3it,} X_{4it}\right) \tag{8}$$

To undertake the empirical estimation, all variables are transformed into their natural logarithm, thus the study specifies the model as

$$\mathrm{LCO}_{2_{it}} = \vartheta_0 + \vartheta_1 \mathrm{LBIO}_{it} + \vartheta_2 \mathrm{LNRR}_{it} + \vartheta_3 \mathrm{LGLO}_{it} + \vartheta_4 \mathrm{LGDP}_{it} + e_{it} \tag{9}$$

where t represents the time span of the study (1980–2018); i denotes the cross section of Congo Basin countries; ϑ for coefficients of the series and ε stands for the error term. LGDP is expected to relate positively with LCO_2 as portrayed at the literature review section, i.e., ($\vartheta 4 = \frac{\vartheta \mathrm{LCO2}}{\vartheta \mathrm{LGDP}} > 0$).

Contrarily, LBIO is anticipated to have a negative association with LCO_2; i.e., ($\vartheta_1 = \frac{\vartheta \mathrm{LCO2}}{\vartheta \mathrm{LBIO}} < 0$). Furthermore, a positive association is envisaged between both NRR, LGLO and LCO_2; i.e., ($\vartheta_2 = \frac{\vartheta \mathrm{LCO2}}{\vartheta \mathrm{LNRR}} > 0$, $\vartheta_3 = \frac{\vartheta \mathrm{LCO2}}{\vartheta \mathrm{LGLO}} > 0$). Where LCO_2 is log of carbon emissions as proxy for environmental quality; LGDP is log of gross domestic product per capita representing economic growth; LGLO is log of economic globalization; LNRR is log of natural resources rent; and LBIO is log of biomass energy consumption.

3.3 Cross-sectional dependence (CSD) and slope heterogeneity Tests

Countries are becoming more and more interconnected to each other and trade barricades are becoming increasingly relaxed in favor of economic, social, and political interdependence. In this regard, there are chances they might have a high cross-sectional dependence. The conventional procedure in panel analysis requires that we check and resolve issues of cross-sectional dependence in secondary data before conducting regression estimation without which, the outcome of the analysis may generate misleading statistical evidence (Adebayo et al., 2021; Awosusi et al., 2022). This study employed the CSD according to Pesaran (2015) as computed in Eq. (10). It serves as prerequisite to choosing between first and second-generation unit root tests under the null hypothesis of no cross-sectional dependence against its alternative of CSD availability. In addition, verifying for slope heterogeneity coefficient is vital, without which the assumptions of slope coefficient of homogeneity may produce deceptive valuation outcomes. In conformity to this assumption, the study utilized Blomquist and Westerlund (2013) and Pesaran and Yamagata (2008) to assess for slope homogeneity/heterogeneity (S–H) in the cross-sectional data. However, both techniques are superior forms of Swamy (1970) as their robustness vary across the ladder from Eqs. (11), (12) and (13). The null hypothesis concedes that slopes are homogeneous while the alternative admits that slopes are heterogeneous.

$$\mathrm{CSD}_{TM}\frac{TN(N-1)^{1/2}}{2}\overline{\rho}_N \tag{10}$$

Here, $\overline{\rho}_N$ represents the parameters of pairwise correlation while N and T represents cross-sectional units in relation to numbers and period respectively.

$$\tilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\overline{S}-k}{\sqrt{2k}}\right) \sim X_K^2 \tag{11}$$

$$\Delta_{\mathrm{HAC}} = \sqrt{N}\left(\frac{N^{-1}S_{\mathrm{HAC}}-k}{\sqrt{2k}}\right) \sim X_K^2 \tag{12}$$

$$(\Delta_{\mathrm{HAC}})_{\mathrm{adj}} \triangleq \sqrt{N}\left(\frac{N^{-1}S_{\mathrm{HAC}}-k}{v(T,k)}\right) \sim N(0,1) \tag{13}$$

S represents Swamy test statistic, N denotes number of cross section units, k represents the independent variables, while Δ_{HAC} and $(\Delta_{\mathrm{HAC}})_{\mathrm{adj}}$ stands for large and small sample size respectively with heteroscedasticity and autocorrelation, and $(\Delta_{\mathrm{HAC}})_{\mathrm{adj}}$ is the "mean–variance bias-adjusted version of Δ_{HAC}.

3.4 Panel stationarity test

An estimator may produce flawed outcome if the parameters in the panel have a unit root (nonstationary), except they have a long-term connection (co-integration) given that panel data incorporates extensive information and variability than pure time series data. Thus a unit root check is essential prior to estimating the long run equilibrium test because it enables us to determine if trending data has to be first differenced or regressed on deterministic function of time to make it stationary. The cross sectional Augmented Dickey Fuller (CADF) and the cross-sectional Im, Pesaran and Shin (CIPS) unit root test Peseran et al. (2013) were utilized as computed. They are both classified as second-generation unit root test because they produce robust outcomes when estimating CSD compared to their first-generation counterparts. The CIPS test is derived from Eq. (14) as follows

$$\widehat{\mathrm{CIPS}} = \frac{1}{N}\sum_{i=1}^{n} \mathrm{CADF}_i \tag{14}$$

The average lagged of the cross section and the first difference of its averages are is denoted by $\overline{Y}_{t-1}$ and $\Delta\overline{Y}_{t-1}$ respectively; CADF refers to cross-sectional augmented Dickey-Fuller.

3.5 Panel test for co-integration

The unit root test outcomes help to determine whether co-integration test should be performed before estimating the long-term association between concerned parameters. If the unit root test is stationary at level, the ordinary least square (OLS) methods is recommended to estimate the long run associations between variables, otherwise (when stationary at first difference), the OLS methods become ineffective to check for variables' co-integration. Here, co-integration methods like the Pedroni (2004) and McCoskey and Kao (1998) can be utilized, although they are less robust in detecting co-integration when there is CSD and slope heterogeneity among variables, as they may produce flawed results. This study utilized the Westerlund (2007) bootstrapped co-integration test, which is innovative and more robust to test for long-term link between variables in presence of CSD and slope heterogeneity. The co-integration test is expressed:

$$\alpha i(L)\Delta y_{it} = y2_{it} + \beta_i\left(y_{it} - 1 - \acute{\alpha}_i x_{it}\right) + \lambda_i(L)v_{it} + \eta_i \tag{15}$$

where

$$\delta_{1i} = \beta_i(1)\hat{\vartheta}_{21} - \beta_i\lambda_{1i} + \beta_i\hat{\vartheta}2_i \text{ and } y2_i = -\beta_i\lambda 2_i \tag{16}$$

The co-integration test statistics according to Westerlund (2007) as expressed in Eqs. (17), (18), (19) and (20)

$$G_t = \frac{1}{N}\sum_{i-1}^{N} \frac{\acute{\alpha}_i}{SE\left(\acute{\alpha}_i\right)}, \tag{17}$$

$$G_a = \frac{1}{N}\sum_{i-1}^{N} \frac{T_{\acute{\alpha}_i}}{\acute{\alpha}_i(1)}, \tag{18}$$

$$P_T = \frac{\acute{\alpha}}{SE(\acute{\alpha})}, \tag{19}$$

$$P_a = T_{\acute{\alpha}} \tag{20}$$

Here, group statistics are denoted by G_t and G_a whereas panel statistics are represented by P_T and P_a. The null hypothesis affirms the absence of co-integration.

3.6 Panel-corrected standard errors (PCSE) estimation

To realize our objectives, the newly developed two-stage modified OLS estimator, called the panel-corrected standard errors (PCSE) is adopted for long-term estimation. In their studies of long-run co-integration, Beck and Katz (2011) proved that PCSE is a robust tool for long-run equilibrium analysis. They claim that the coefficients between feasible generalized least squares (FGLS) and PCSE models are close and only the constants substantially differ. Nevertheless, since we are interested in the constant, PCSE with OLS model is chosen. The estimator uses modified GLS estimates, which can preserve weights and correct inherent cross-sectional errors using sandwich estimates. The approach also is well-suited for large N and short T balanced panel data with cross-sectional dependence (Bailey & Katz, 2011). The PCSE approach for testing long run co-integration properties have been confirmed as yielding robust estimates (Ikpesu et al., 2019). The approach is robust to heteroskedastic, contemporaneously cross-sectional correlated, and auto-correlated of first-order auto-regression.

Accepting that the blunders in the OLS model (Eq. 7) are time-related autonomous, the change covariance framework of the errors can be constructed as

$$\cap = \sum \otimes 1\mathrm{r} \tag{21}$$

where Σ is the $N \times N$ lattice of mistake differences and contemporaneous co-variances and $\bigotimes$ address the Kronecker item. Given Σ refer to the $T \times N$ grid of the OLS residuals. $E'E/T$ gives a predictable gage of Σ. PCSEs are accordingly assessed by the square base of the askew of

$$(X\prime X)\prime X'\left(\frac{EE}{T} \otimes I_r\right)X(X'X)^{-1} \tag{22}$$

In the final processes, the study checks model robustness with fully-modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) approaches; and use Dumitrescu Hurlin estimator for causality test.

4 Empirical outcomes, discussion and limitations

4.1 Empirical outcomes and discussion

4.1.1 Descriptive statistics

The paper has used standard econometric processes and methods for this analysis, beginning with descriptive statistics of the interest variables. Table 2 is the illustrative summary and statistical description of all variables employed for this study.

With significant P values for all the variables, the study rejects the null hypothesis of abnormal distribution at 1%, level of significance.

The outcomes of descriptive assessment (Table 2) show no outliers in the dataset. The outcomes also indicate variables are normally distributed, paving way for further

Table 2 Descriptive statistics. *Source*: Prepared by authors

	LCO_2	LGDP	LBIO	LGLO	LNRR
Mean	−0.308011	3.277278	7.186620	1.616900	1.214428
Median	−0.225249	3.258190	7.165446	1.643663	1.281474
Maximum	0.960613	3.994291	8.175056	1.734309	1.657841
Minimum	−1.787474	2.523767	6.189962	1.407576	0.696919
SD	0.736149	0.437299	0.656845	0.080423	0.257957
Skewness	−0.331930	0.132185	0.021809	−0.579276	−0.372404
Kurtosis	2.209827	2.054522	1.341553	2.437618	1.951056
Jarque–Bera	6.923047	6.264832	17.89028	10.78037	10.75764
Probability	0.031382	0.043612	0.000130	0.004561	0.004613
Sum	−48.04970	511.2554	1121.113	252.2364	189.4508
Sum sq. dev	83.99696	29.64074	66.87394	1.002510	10.31395
Observations	156	156	156	156	156

estimation activity. The next step involves carrying further pre-estimation checks, including assessing panel CSD and unit root features of the variables considered for the study as explained in the data and methods section.

4.1.2 Cross sectional dependence (CSD) and slope homogeneity estimates

From Table 3, the *p* values are significant for the CSD estimates. These outcomes declines the null hypothesis at 1% significance level, thus affirming the existence of CSD in the panel. Furthermore, the calculated *p* values are all significant for the slope homogeneity estimates, indicating a rejection to the slope homogeneity assumption, and rather accepting slope heterogeneity alternative for the panel. This outcome supports similar findings by (Campello et al., 2019).

Table 3 Cross section dependence (CSD) and slope homogeneity estimates. *Source*: Prepared by authors

Cross sectional dependence

Test	CO_2	GDP	BIO	NRR	GLO
Breusch–Pagan LM	57.30593*	63.22192*	202.6019*	59.90900*	177.7869*
Pesaran scaled LM	14.81075*	16.51855*	56.75407*	15.56219*	49.59060*
Bias-corrected scaled LM	14.75811*	16.46591*	56.70144*	15.50956*	49.53797*
Pesaran CD	−0.264999	7.171381*	14.22580*	5.947558*	13.32351*

Slope homogeneity

Pesaran and Yamagata (2008)			Blomquist and Westerlund (2013)		
Tests	Delta value	*P* value	Tests	Delta value	*P* value
	6.558 *	0.000		3.698 *	0.000
adj	7.129 *	0.000	adj.hac	4.021 *	0.000

The star * indicates *p* values that are significant at 1%

Table 4 Cross sectional ADF test/cross sectional IPS test. *Source*: Prepared by authors

Variables	CIPS		CADF	
	I(0)	I(1)	I(0)	I(1)
LCO_2	−2.805*	−5.328*	−2.864*	−5.034*
LGDP	−2.809*	−4.216*	−2.676**	−3.098*
LBIO	−2.371**	−5.805*	−2.176	−4.897*
LNRR	−4.245*	−6.190*	−3.823*	−5.503*
LGLO	−2.657*	−5.485*	−3.003*	−4.107*

**p* values significant at 1%; I(0) means a stationary process whose long-run variance is finite and positive; An I(1) process is a difference-stationary process (or, a unit-root process)

Table 5 Westerlund (2007) bootstrapped co-integration estimates. *Source*: Prepared by authors

Statistic	Value	*Z*-value	*P* value	Robust *P* value
Gt	−3.372	−1.120	0.131	0.070
Ga	−9.127	1.906	0.972	0.350
Pt	−6.330	−1.076	0.141	0.050
Pa	−8.750	1.194	0.884	0.280

4.1.3 Unit root estimates

The results (Table 4) indicate all variables are integrated at level ($I(0)$) under lag 2, based on AIC; and this outcome allows rejecting the null hypothesis of panel containing unit roots at 1% level of significance. This outcome is similar to those reported by (Adebayo et al., 2021). The result also enables the consideration of second-generation Westerlund (2007) bootstrap co-integration estimator for next action due to cross-sectional dependency, slope heterogeneity, autocorrelation and heteroscedasticity factors.

4.1.4 Co-integration estimates

Table 5 reports an estimate of co-integration analyses using Westerlund (2007) bootstrapped second-generation-based co-integration estimator. Both between and within-dimensions outcomes are reported, and they reject the null hypothesis of "no co-integration" in the presence of cross-sectional dependence, slope heterogeneity and serial correlation. Based on Table 5, Gt (−3.372, $p<0.070$) and Pt (−6.330, $p<0.050$) are significant at 5% and 10%, respectively. This is evidence of a co-integrating association between CO_{2it}, $LBIO_{it}$, $LNRR_{it}$, $LGLO_{it}$ and $LGDP_{it}$, thus the ECM for this model is expressed as $\frac{P_a}{T} = \frac{-8.750}{38} = -0.23$. Improbability in the short-term will be resolved at 23% in the long-run. On this note, long-run investigations can be conducted on the determinants of CO_2 emissions in the Congo Basin panel.

4.1.5 Long-run equilibrium PCSE estimates

The long-run equilibrium PCSE estimates indicate that LBIO exerts negative effects on LCO_2, given that the coefficient of LBIO is negative and significant. Per the outcomes (Table 6), a unit rise in LBIO leads to a corresponding reduction in LCO_2 by − 0.503435% in the Congo basin. This finding validates hypothesis 1 (H_1) that "biomass energy use enhances the quality of the environment in the Congo basin." These outcomes show that biomass energy can serve as a perfect solution for renewable energy since it decreases CO_2 emissions across the Congo Basin. This result supports the empirical findings of Wahlund et al. (2004) in Sweden. Further, Suttles et al. (2014) tested the global computable general equilibrium model in the European Union and the US and found bioenergy use to reduce CO_2 emissions. According to an analysis

Table 6 Panel-corrected standard errors and covariance (PCSE), FMOLS and DOLS estimates. *Source*: Prepared by authors

Long-run estimation-Panel-corrected standard errors (PCSE)				
Variable	Coefficient	SE	*t*-statistic	Prob
C	− 3.658343	1.146529	− 3.190799	0.0017*
LGDP	1.523498	0.159192	9.570180	0.0000*
LBIO	− 0.503435	0.136666	− 3.683688	0.0003*
LGLO	1.095417	0.362421	3.022500	0.0030*
LNRR	0.168162	0.076697	2.192554	0.0299**
R-squared				0.958309
Adjusted *R*-squared				0.956337
SE of regression				0.153824
Robustness check-FMOLS				
Variable	Coefficient	SE	*t*-statistic	Prob
LGDP	1.571809	0.228292	6.885093	0.0000*
LBIO	− 0.551593	0.251011	− 2.197484	0.0296**
LNRR	0.238843	0.129423	1.845443	0.0670***
LGLO	1.093609	0.596769	1.832549	0.0689***
R-squared				0.959480
Adjusted *R*-squared				0.957510
SE of regression				0.151857
Robustness check-DOLS				
Variable	Coefficient	Std. Error	t-Statistic	Prob
LGDP	2.116510	0.125677	16.84084	0.0000*
LBIO	− 1.265372	0.341757	− 3.702546	0.0009*
LGLO	2.063805	0.668045	3.089321	0.0045*
LNRR	0.360929	0.181867	1.984571	0.0571***
R-squared				0.995373
Adjusted *R*-squared				0.978352
S.E. of regression				0.108806

*, **, ****p* values are significant at 1%, 5% and 10%, respectively

submitted to the Forest Carbon Partnership Facility regarding country-based REDD+ strategies and REDD+ readiness proposals, determined environmental improvement actions had been taken by countries across the Basin. These include among others, the implementation of VPA-FLEGT, energy efficiency campaigns, the establishment of wood fuel energy plantations, climate-smart agriculture and certification of agricultural plantations (Enongene & Fobissie, 2016). For the Congo Basin to achieve SDGs 7, 13 and 15, fresh investments in modern biomass energy production are primordial given that biomass is readily available across the region and its combustion is environmentally friendly. Given its biomass generation potential in the region, investments in research and development toward renewable energy generation are the best starting point for governments across the enclave.

Additionally, the long-run equilibrium PCSE co-integration estimates (Table 6) indicate that the coefficient of LNRR is positive, indicating that LNRR exerts positive effects on LCO_2. Realistically, the outcomes indicate that a unit rise in LNRR leads to a matching upsurge in LCO_2 by 0.168162% in the Congo basin. By implication, notwithstanding numerous policies and institutions in place across the region, environmental quality is threatened. Policies are required to improve institutional and regulatory quality across the Congo Basin. This finding validates hypothesis 2 (H_2) established for the study that "natural resources rent leads to declining environmental quality in the Congo basin." The finding also confirms a similar finding by Kwakwa et al. (2020) for the case of Ghana from 1971 to 2013. It also confirms similar findings by Sibanda et al. (2023). It is significant to emphasize that natural resources rented for mining and other extractive projects in the Congo basin would directly facilitate economic growth in the sub region. However, several studies have confirmed heavy environmental destruction are associated with such projects. Additionally, using fossil fuels for extractive exploration and production activities contributes substantially to pollution and CO_2 emissions rise (Bekun et al., 2019). Awosusi et al. (2022) investigated natural resources rented and excessive usage of heavy machinery for production and found serious environmental problems associated with deforestation, water pollution and global warming. A project-based study conducted on natural resource rent at the operation center for Konkola Copper Mines (KCM), in the Chinogola District of Zambia and at Lubumbashi in the DRC where mineral extraction activities abound, found heavy destruction of the forest, rising poverty levels and serious environmental concerns. These outcomes establish the need to improve natural resource efficiency while concurrently reducing its nefarious effects on the ecosystem by levying heavy environmental fines on extracting firms.

The long-run equilibrium PCSE estimates indicate that LGLO exerts positive effects on LCO_2 as the coefficient of LGLO has a positive value and is significant. The outcomes as illustrated in (Table 6) indicate that every unit increase in LGLO results in a conforming rise in LCO_2 by 1.523498% in the Congo basin. This result validates hypothesis 3 (H_3) established for this study (Hypothesis 3 (H_3), economic globalization helps to destroy environmental quality in the Congo basin. Nwonwu (2005) finds that across the Congo Basin, globalization has caused excessive forest exploitation and degradation. To complement the international community's green forest policy support, governments across the enclave could take effective investment and policy actions on aspects of globalization that lead to environmental degradation. It must be emphasized that such actions should be considered combination with measures, including stakeholder participation, combat corruption, institutional strengthening and development of sustainable forest management standards.

Further, the long-run equilibrium PCSE estimates indicate that LGDP exerts positive effects on $LCO_{2,}$ as the coefficient of LGDP is positive and significant. The outcomes as illustrated in (Table 6) indicate that every unit rise in LGDP leads to a corresponding rise in LCO_2 by 1.523498% in the Congo basin. This result validates hypothesis 4 (H_4) established for this study and supports the EKC framework proposed by Grossman and Krueger (1995). By the EKC framework, this outcome signifies that economies across the Congo Basin have given priority to economic growth over its detrimental effect on environmental degradation and pollution. According to Hilaire and Fotio (2015) evidence has been found that CO_2 emissions increased by 81% between 1990 and 2000 across the Congo Basin. Bakehe and Hassan (2021) found that economic growth has been responsible for the destruction on forest and other protected areas across the Congo Basin. However, Aquilas et al. (2022), could not find an inverted U-shape relationship between deforestation and GDP in the region.

4.1.6 Robustness check with FMOLS and DOLS

The strength of the FMOLS and DOLS models as illustrated in Table 6 indicates that the predictors (i.e., LGDP, LBIO, LNRR & LGLO) collectively explain 99.94% of LCO_2 (i.e., the dependent variable) for FMOLS estimates and 99.53% for DOLS estimates in the Congo basin. Pedroni (1999) claims that annoyance constraints in regressions could create endogeneity and serial correlation problems leading to biased estimates. By focusing on nonparametric processes, both the DOLS and the FMOLS estimators are effective in getting rid of endogeneity and autocorrelation errors in heterogeneous panels.

4.1.7 Panel causality estimates

The outcomes of D-H causality (Table 7) indicate (i) unidirectional causality running from LGDP to LCO_2 without rebound effect. (ii) Unidirectional causality running from both LNRR and LGLO to LGDP without rebound effect. (iii) Unidirectional causality running from LGLO to LBIO without rebound effect. These results imply that both LNRR and LGLO directly cause LGDP growth, which eventually causes LCO_2. These outcomes are in line with the EKC frame regarding economic globalization and pollution Grossman and Krueger (1995) and the pollution haven hypothesis regarding the adverse effects of globalization on environmental quality Dinda (2006). The overall outcomes of this study are summarized in Fig. 5.

4.1.8 Managerial implications and practical insights of the study

In this study, we investigated the effects of biomass energy use on environmental quality in the Congo Basin. The outcomes suggest that biomass energy use enhances the

Table 7 Dumitrescu Hurlin causality estimates. *Source*: Prepared by authors

Causal orientation	W-Stat	Zbar-Stat	Prob
LGDP → LCO_2	5.79334	3.20965	0.0013*
LGLO → LGDP	4.44123	2.02392	0.0430**
LNRR → LGDP	5.33242	2.80544	0.0050*
LGLO → LBIO	4.44049	2.02326	0.0430**

* and **Statistical levels of significance at 1% and 5%, respectively

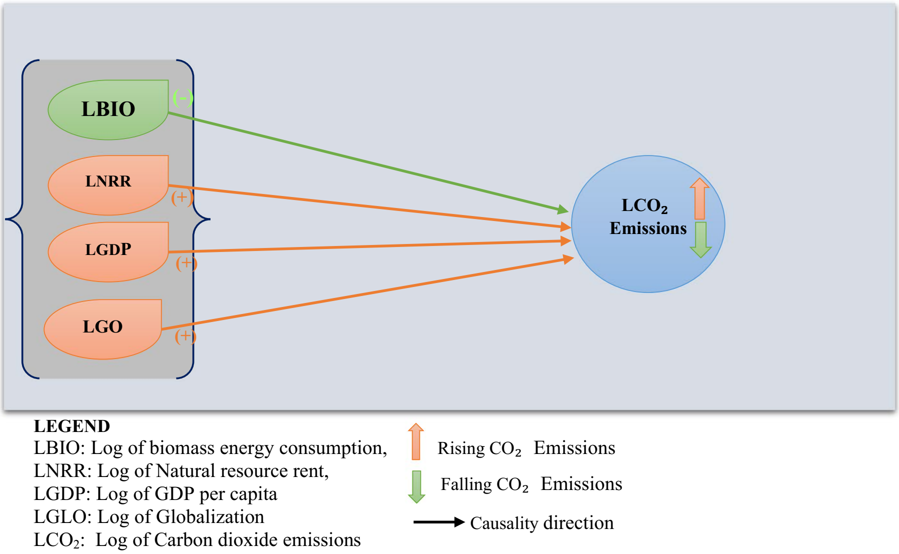

Fig. 5 Graphical outcome of PCSE, FMOLS, DOLS and D-H panel causality. *Source*: Prepared by authors

quality of the environment. Therefore, governments across the Congo Basin should increase investments in renewables especially modern biomass energy since it is freely available and its combustion is less harmful to the environment. This concords with the United Nations SDGs 7, which emphasizes the need to minimize fossil fuel use and switch to affordable and clean energy such as modern biomass, which has the potential to reduce the nefarious effects of climate change (SDGs 13).

To better maximize its biomass energy potential, Congo Basin countries need a cross-sectional and multi-disciplinary partnership to scale up bioenergy technology and make it feasible.

Furthermore, given that natural resource rents, globalization and economic growth deteriorate environmental quality in the Congo Basin, governments across the enclave are required to invest rents from foreign trade and foreign direct investments into renewable energy projects especially modern biomass. The Kindergarten Rule model (Brock & Taylor, 2003) highlights that economic growth spearheaded by renewable energy production and consumption like modern biomass has a very high potential to boast environmental quality as opposed to growth championed by fossil energy consumption.

To manage waste from natural resource extraction, wastewater generated during natural resource extraction could be treated and reused for drinking, showering, dust suppression and material processing as a coolant. To operate sustainably, while valuing wastewater requires that planning should include such usability factors in the design of the extraction project.

For these to materialize, policies are needed to ensure institutional and regulatory quality across the Congo Basin.

4.2 Limitations of the study and directions for further research

The limitations of this paper point to the few variables of interest considered for this research. The authors are of the view that due to the systemic nature and complexities involved in determining pollution and abatement policies, several other variables could be considered for future investigations. Future studies could also consider other comparable basins across the world, given that the reality of the asymmetric effect of natural resources rent and biomass energy use may differ based on context, policy options and applicable technological innovation.

In addition, future research could consider focusing on the qualitative variables within countries or in the entire basin while comparing the outcomes with the ones obtained in this study. Such studies could be project-based research, involving multiple disciplines and stakeholders or actors. By so doing, the uneven impact on different social groups and regions would be identified, assessed and addressed.

5 Conclusion and policy recommendations

The UNFCCC signatories agreed at COP21 in Paris to confront issues that compromise environmental quality, especially climate change and to speed up policies and investments to ensure a sustainable future for humanity and the planet Earth. To support relevant policies and contribute to environmental literature, this paper assesses the asymmetric impacts of biomass energy use on environmental quality in the Congo Basin from 1980 to 2018 using a blend of enhanced empirical methods such as the PCSE, FMOLS and DOLS. The Westerlund (2007) bootstrapped co-integration estimates indicate that variables are co-integrated. The estimated panel-corrected standard errors suggest (i) Biomass energy use promotes environmental quality; (ii) Natural resources rent, economic growth and globalization exert a deteriorating effect on environmental quality; (iii) The Dumitrescu Hurlin causality test indicates both natural resources rent and globalization indirectly affects environmental quality through economic growth.

These results contribute to existing environmental literature in several ways. First, studies incorporating CO_2 emissions are limited in the Congo despite its carbon reduction potential globally. Second, the emissions reduction capacity of biomass energy utilization is detected in the Congo Basin, holding other variables under control over the study period. Third, this represents the first time the PCSE method is employed to examine the state of environmental quality in the Congo Basin. Fourth, compared to other empirical investigations, both DOLS and FMOLS methods are employed to ensure the model reports reliable outcomes for policy suggestions; Fifth, the paper employs the novel Kindergarten Rule model which complements other growth-related theories and can highlight the effect of endogenous technological progress in pollution abatement, which help corporations reduce compliance costs despite rising production. These outcomes provide significant policy insights to the governments across the Congo basin.

Policymakers across the region could in the short-term use efficient biomass technologies while shifting energy-sourcing policies toward renewable energy technologies eventually. Furthermore, initiatives to curtail deforestation are implausible, and member states of this Basin are yet to differentiate principal causes from distant drivers. Therefore, economies across the Congo Basin enclave desiring to benefit fully from their natural resources should identify and categorize drivers of deforestation and strengthen regulatory institutions to guide sustainable economic growth.

For the irresponsible side of globalization, regulatory institutions could be empowered to impose restrictions or impose fines and taxes on emission-intensive investments, typically extractives across the enclave. To lessen the effects of globalization and output across the Basin, environmental innovation is inevitable and achievable through research and development, whereas investments in biomass energy use, according to the outcome of this study could strengthen environmental quality in the entire Basin. For this to be effective, cooperation and political commitments are required for Congo Basin governments to incorporate and foster sustainable development goals that could align their socioeconomic plans with low-carbon development policies.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval The authors confirmed that this manuscript has not been published somewhere else and is not under consideration by another journal. Thus, informed consent and ethical approval do not apply to this research.

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