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Research Paper

Assessing the palliative aspects of green innovations in the non-linear tendencies of environmental sustainability-financial globalization nexus among West African states

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A B S T R A C T

A reconciliation of the disagreement on whether financial globalization (FG) affects ecological footprint through the scale, technique and composition effects cannot be achieved without an explicit understanding of the direct and indirect interactions of FG with environmental sustainability. Hence, the novel perspective of this study lies in the investigation of how green innovations moderate the non-linear tendencies in the FG-environmental sustainability link among western African states given the abundance of natural resources and the prevailing pace of economic growth. The core findings are obtained from robust analysis based on cross-sectional autoregressive distributed lag (CS-ARDL) technique, the augmented mean group (AMG) technique, and the common correlated effects mean group (CCEMG) advanced estimators. Firstly, the beneficial ecological impacts of green innovations were observed. As per direct impact, enhanced financial globalization (FG) exhibits non-linear detrimental ecological effects. However, green innovations cushion the observed adverse ecological effects of FG. Furthermore, resource rents reduce ecological footprint within the moderating framework of green innovation as the environmental Kuznets curve (EKC) is validated among the states. Additionally, a bidirectional causal link between financial globalization, green innovations, economic growth, natural resources, and ecological footprint was observed. Thus, the significant policy implication is for the West African states to decisively increase their investments in green innovations while strategically encouraging the share of ecologically friendly resources in total resource utilization to guarantee a more sustainable environment.

1. Introduction

Climate change and environmental degradation are among the leading negative externalities of economic growth and urbanization. In this vein, the idea of global sustainability encompassing the three distinct areas: economy, environment, and society has been hotly debated in the context of West African (WA) states as the region's gross domestic product per capita grew in recent decades (AfDB, 2012). Also, the Africa Sustainable Development Report (ASDR, 2022) shows that some economic gains and progress have been made over the years within the global sustainable development agenda to which African nations are committed to. However, considering that global sustainability does not entail only the economic and societal areas, the environmental pillar remains a focal point of challenge in attaining the targets of Sustainable Development Goals (SDGs) in the African continent. There has been a decline in environmental quality in various regions across the globe and countries in the West Africa region are not an exemption. As such, many recent studies have attempted to explain the various environmental indicators that influence greenhouse gas (GHG) emissions (Verbič et al., 2022). Even though anthropogenic emissions threaten human health, pollute sea levels, and cause catastrophic weather conditions, they do not comprehensively capture all pollution in the environment (Danish et al., 2019; Hassan et al., 2020). Against this backdrop, Wackernagel and Rees (1996) introduced a more holistic measure of environmental degradation, namely ecological footprint (EFP) which captures not

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only pollutant emissions but also the other indicators of environmental degradation such as deforestation and biodiversity loss among others. Ecological footprints outline the amount of natural resources used globally by mankind, city, region, or country to meet human needs. It also shows the effects of human-specific activities on the available natural resources and the environment at large (Danish and Hassan, 2022).

The pertinent motivation for the current study essentially lies within the unique context of the West African states given their extreme vulnerability to environmental challenges that hale from climate change. Although the growing climate vulnerability applies to the entire African continent, the West African (WA) region in particular has been experiencing increasing EFP over the years. Also, many other places across the globe have been reported to be confronted with rapid climate challenges like in Latin America (Alvarado et al., 2021), the emerging seven economies (Gyamfi et al., 2023), and China (Alola et al., 2021) among others. In the period 1961 to 2008, the EFP of Africa increased by 240% (AfDB, 2012) as the continent was expected to be in a biological deficit as of 2015. According to statistics from the Global Footprint Network (GFN) depicted in Figs. 1 and 2, the EFP and biocapacity of WA had an increasing trend from 1961 to 2019. However, the biocapacity of the region from 1961 to 1997 was higher than its EFP resulting in ecological reserve as displayed in Fig. 3, but the region's EFP from 1998 to 2019 was higher than its biocapacity leading to ecological deficit. The increasing ecological deficit of WA indicates that anthropogenic human activities in the region are detrimental to ecological sustainability.

The leading determinant of the bloc's rising EFP is the upswing in consumption resulting from economic growth and population rise (Onifade, 2023). As higher consumption levels are potentially detrimental to environmental quality and intensified use of natural resources degrades the ecosystems, West African states evolve as an attractive laboratory to investigate the environmental aspects of the sustainable development discussion. An alternative motivation for focusing on the West African bloc in this study is the status of most countries in the region as natural resource-dependent economies. The region's resource abundance has been argued to be contributing to the rise in ecological footprint and loss of biological capacity which is compromising the hope of a sustainable future in the area (Obuobi et al., 2022). Some other unique attributes of WA motivated us to undertake this study. Firstly, emissions are increasing dramatically across the region posing serious implications for human health. Secondly, urbanization and economic development in the bloc have been on an increasing trend for decades with a corresponding increase in ecological pollution (Erdoğan et al., 2022). Thirdly, although the African continent is abundant in renewable energy sources, it is characterized by technological inefficiency, research and development deficiency, an underdeveloped financial sector, corrupt institutions, energy poverty, and scarcity of innovative technologies (Obobisa et al., 2022). However, these factors have not been properly examined within the ecological sustainability context of the WA region and this study subsequently helped to fill that gap. Consequently, to reach solid research-based conclusions for well-informed policy, the study attempts to investigate whether green innovations (GI) might be effective in enhancing environmental quality by abating the adverse environmental impact of financial globalization (FG) in the WA states.

From the standpoint of policymaking, a proper understanding of the region's ecological footprint dynamics is vital in helping investors, businesses, and governments to realize the environmental outcomes of their activities to embrace greener approaches for sustainable development. The current study is also important to help stakeholders in directing substantial actions to the depletion of environmental performance by leveraging green innovations in dealing with environmental degradation more sustainably. In this vein, we aim to comprehend the nexus amid financial globalization, green innovations, income, and ecological footprint in the context of West African states. As the exploration of the determinants of ecological footprint in the western region of Africa is scarce, the policy discourse proposed is useful in stimulating the need to place green innovations on top of the climatic change mitigation agenda. Herein, our study assesses the role of several factors in combating environmental pollution.

To begin with, among others, financial globalization (FG) is a valuable tool for combating environmental degradation. Prasad et al. (2003) defined FG as an aggregate concept that expresses rising worldwide associations actualized through cross-border financial flows. It does not only influence capital mobility but also

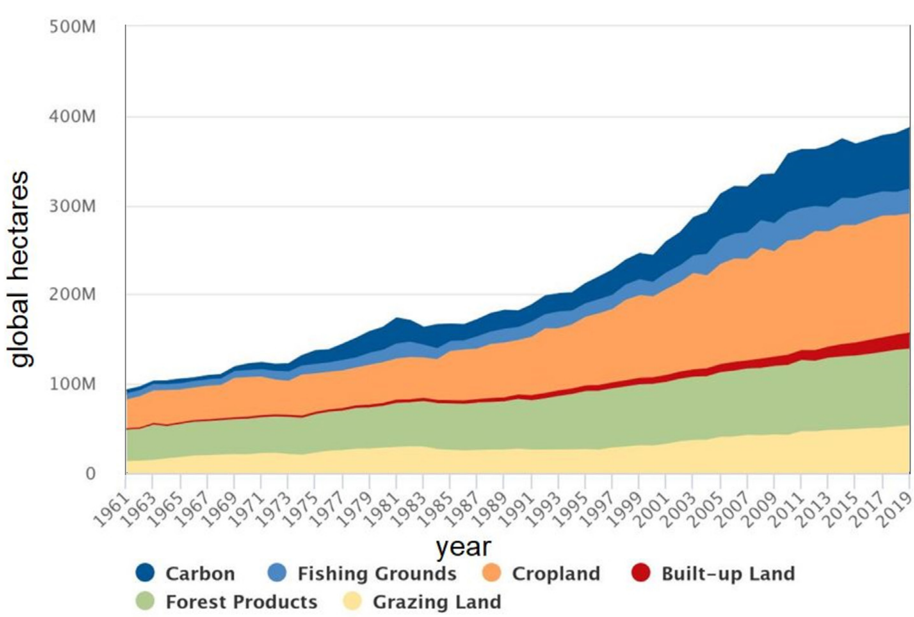

Fig. 1. West Africa's ecological footprint.

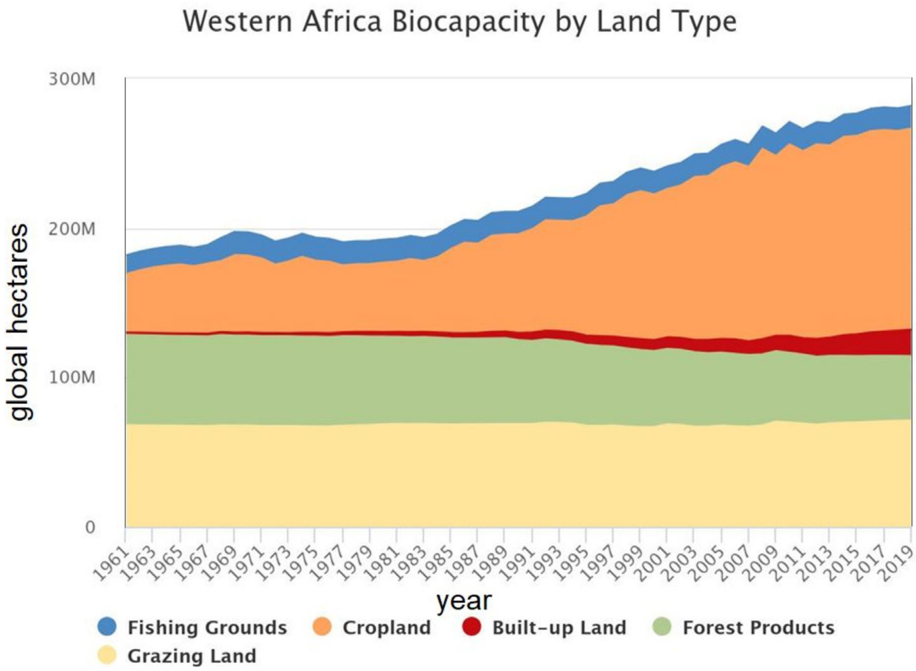

Fig. 2. West Africa's biocapacity.

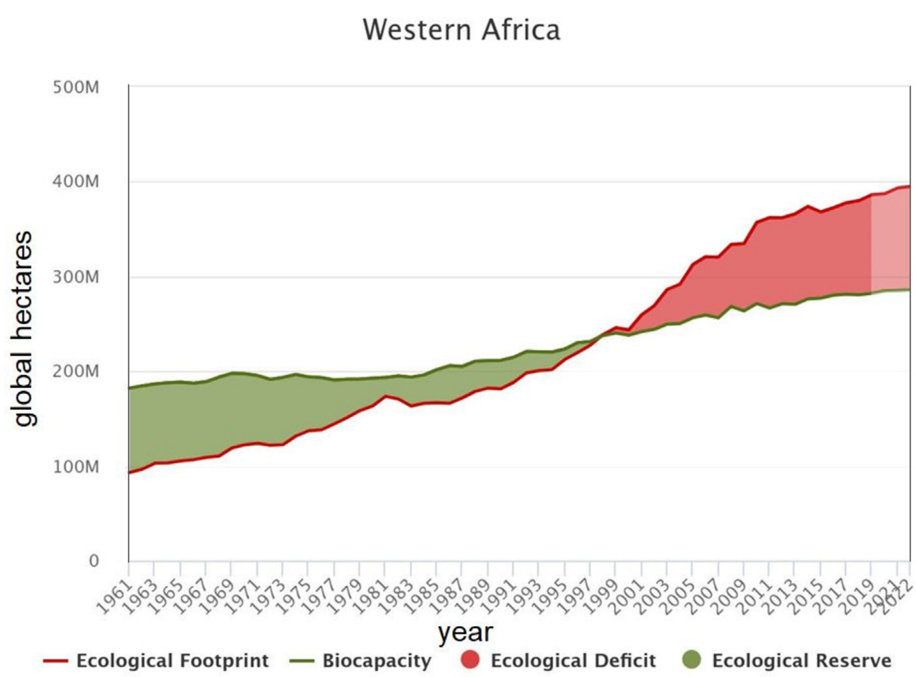

Fig. 3. West Africa's ecological deficit and ecological reserve.

channels the impact of economic growth on environmental sustainability (ES) (Ilham et al., 2021). Financial globalization enhances the interaction between countries, international firms, and financial institutions influencing the EFP of exporting and importing countries. It represents a good means of coping with environmental degradation and forms part of financial liberalization and trade openness giving governments alternatives for environmentally friendly and cost-effective solutions. FG also plays a prominent role in developing countries (Chen et al., 2023). Specifically, these nations have made moves to transition from agriculture to technologically sophisticated economies. This shift is accelerated by FG, which has promoted foreign finance, advanced technologies, managerial expertise, and competitive advantage in developing economies (Ahmad and Satrovic, 2023a). Globalization is also beneficial for rising market competition and avoiding monopolistic behavior. In summary, through the scale effect, financial globalization hampers environmental performance by boosting investments in industrial and other economic activities that are operating in an unsustainable manner. Also, via the technique and composition effects, FG might be helpful in driving investments in green energies, technological innovations, and energy-saving initiatives that help in tackling climate change.

As for green innovations (GI), they are viewed as critical factors that could help to attain the SDGs in the growing literature, herein worldwide economies have currently focused on GI to explain the dynamics in economic growth and environmental pollution. As suggested by Damrah et al. (2022a), GI can help mitigate environmental degradation by implementing eco-friendly technologies. In other words, GI improves the efficiency of energy while motivating a decrease in anthropogenic emissions from industrial processes. In their study, Wen et al. (2022) showed that GI does not only promote green techs but lowers environmental protection costs too. In addition, Li et al. (2022) suggested that GI is beneficial for improving energy efficiency and reducing anthropogenic emissions. As such, GI lowers pollution by cutting the consumption of dirty fuels (Onifade and Alola, 2022); and increasing the share of ecologically friendly resources, and waste recycling (Abid et al., 2022). Innovations include effective business practices, new production techniques, and products and services that benefit individuals and the environment (Chang et al., 2023). Due to globalization, modern technologies are relocated from developed to developing nations. Herein, our study examined whether green innovations moderate the impact of financial globalization on ecological footprint. In the case of the negative sign of interactive term, our study will inflict that green innovations are effective in alleviating the adverse environmental impact of FG whereas the positive sign will signal that developed countries are actually shifting environmental unfriendly technologies that are responsible for an increase in environmental degradation.

This study's theoretical argument is built on the environmental Kuznets curve (EKC) theory by relating the income growth in the region to the ecological footprint. The EKC phenomenon hypothesizes an inverted U-shaped linkage amid income and ecological depletion. This means that, initially, income reduces environmental quality, but at higher levels, any further rise in income helps to curb environmental pollution. The natural resource rents were incorporated within the EKC framework as a control variable to help curtail the implications of model misspecification since the area is also rich in resources (Onifade, 2022). On one hand, increased natural resource extraction can exert pressure on the environment, which can subsequently raise ecological degradation (Sarwat et al., 2022). Besides, it has been suggested by Kwakwa et al. (2020) that the over-exploitation of resources could impede environmental quality because of the anthropogenic emissions associated with machinery used in the extraction and disposition of wastes. In contrast, natural resource abundance can also attract foreign direct investments associated with environmentally friendly technologies that help to abate environmental pressures (Satrovic et al., 2023). Hence, studying the roles of these factors in the ecological sustainability of the WA region was deemed appropriate. Finally, we observe the nonlinear linkage between FG and ecological footprint. The inverted U-shaped pattern will be confirmed if the sign of FG is positive and the sign of its squared term is negative showing that ecological footprint rises with a boost in FG to the threshold point, after which, FG is effective in spurring the environmental quality of West African states.

Based on the above background, the following research questions were formulated to guide the study's conduct; (1) does financial globalization explain environmental sustainability in West Africa? (2) does the interaction between financial globalization and green innovations influence ecological sustainability in West Africa? (3) are financial globalization and ecological sustainability nonlinearly related? Reconciling these puzzles will enable policy designs for net-zero emission targets of the region. The study provides three significant contributions to the literature. First, considering the research objective, this study attempts to establish a conceptual policy coherence that will assist West African states in promoting sustainable development and fostering green innovations expressing a policy-level contribution of the study. This policy coherence strives to attain the targets of SDG 7 and SDG 13, by benefiting from the environmental betterment impact of green innovations. While the policy coherence established in the present study refers to West African states, it can be extended to the other developing states that are tackling environmental degradation issues. Second, this is the pioneer study to examine the interactive effect of GI and FG on ES in the region. The exploration of the interactive effect is of critical importance to ensure that the regions' financial globalization and green innovation targets are carried out in a way that does not jeopardize their ability to sustain their economies. If the interactive term is negative, this will clearly signal that foreign capital should be used to support sustainable production. Herein, policymakers will be enhanced to benefit from financial globalization by increasing funding for green technologies and research and development. Lastly, by testing the nonlinear link between FG and ecological footprint, the study will pave the way for policymakers to capitalize FG for better investments in green and energy-efficient technologies to help boost ecological quality in the region if the link between FG and ecological footprint turns to follow inverted U-shaped pattern.

The remainder of the study is structured as follows; the second portion scrutinizes the recent literature and establishes the research hypothesis of the study. Section 3 highlights the data, model specifications, and methodology. Empirical outcomes and a thorough discussion of the findings are covered in Sections 4 and 5, whereas conclusions and policy implications are presented in Section 6.

2. Literature review

The survey of the literature has been classified under three main sub-headings: (1) financial globalization-environmental indicators nexus; (2) innovative technologies-environmental indicators nexus; and (3) natural resources-environmental indicators nexus.

2.1. Financial globalization-environmental sustainability nexus

The first sub-heading focused on the studies that have looked into the association between FG and ecological indicators. Those studies considered various country samples and methodologies to provide inconclusive and mixed findings. Over the period from 1974 to 2016, Ulucak et al. (2020) investigated emerging economies and disclosed that FG was harmless to ecological quality. In particular, FG improved ecological quality, but the EKC conjuncture could not be validated in the economies. Likewise, Miao et al. (2022) examined newly industrialized countries. In line with MMQR estimates, a negative coefficient for FG was unveiled. To be more specific, financial globalization is beneficial for environmental quality indicating that the policymakers of newly industrialized countries should promote financial liberalization and ease the international flow of capital. Moreover, Farouq et al. (2021) conducted a study on SSA countries from 1980 to 2019. Using the theoretical underpinnings of the environmental Kuznets curve hypothesis, the authors unveiled the positive environmental impact of financial globalization. In other words, the coefficient with financial globalization is negative meaning that international capital is of key importance to support the development of environmentally friendly technologies. Financial globalization has also been found to be effective in stimulating the environmental quality of BRICS countries (Chen et al., 2023). Particularly, in supporting the technique effect, financial globalization is found to be responsible for the fostering of green innovations for attaining the targets of sustainable development. In contrast, Sadiq et al. (2022) confirmed FG as harmful to the ecosystem of BRICS economies. Even though financial globalization eases access to capital and boosts economic emancipation (Haouas et al., 2022), it also causes an upswing in energy use thus leading to environmental degradation, especially among emerging economies. Similarly, Wang et al. (2022) divulged the adverse environmental impact of financial globalization positing that FG is not favorable for the environment of the One Belt One Road countries. Considering the prospect of China, Shahzad et al. (2022) showed a positive association between financial globalization and environmental deterioration. Due to its beneficial role in boosting environmental performance, financial globalization is divulged to have an adverse environmental impact in China.

2.2. Green innovations-environmental sustainability nexus

The second sub-heading investigated the link between innovative technologies and environmental indicators. For instance, Damrah et al. (2022a) considered the period from 1995 through 2019 to analyze whether access to technology leads to the environmental preservation of top oil exporting countries. The findings of the paper confirmed a negative association between technology and carbon intensity. In other words, innovative technologies are used as resources to curb anthropogenic emissions of the inspected sample. The findings of Wan et al. (2022) clearly showed that innovative technologies levy environmental pressure by reducing the energy consumption needs that are met by fossil fuels. They concluded that innovation in eco-friendly technologies reduces carbon dioxide emissions of emerging countries considering the period from 2007 to 2018. This is because green innovations are paving the way for the efficient implementation of eco-friendly technologies that could drive down carbon dioxide emissions and attain the net-zero emission objective of the region. In the same vein, Wahab et al. (2021) analyzed whether innovative technologies benefit individuals and the environment. Using the case study of G7 countries in the period 1996–2017, they found an inverse connection between innovations and pollutant emissions. Herein, the authors recognized the need to promote innovative technologies and green production to decouple environmental pressure. This study shows that technological innovation is effective in promoting environmental sustainability. According to Chang et al. (2023), green innovations can curb carbon dioxide emissions in China. In particular, the authors divulged that green innovations are a vital factor in explaining the environmental betterment of China as they enhance energy productivity, encourage production efficiency, and stimulate the production and consumption of eco-friendly items. Moreover, technological innovations curb environmental degradation by reducing the energy consumption that comes from non-renewable resources (Wen et al., 2022); and increasing the share of ecologically friendly resources, and waste recycling (Abid et al., 2022). Green innovations proved to be an effective tool in abating the carbon dioxide emissions of leading economies as they reduce the dependence on fossil fuels and enhance the use of renewable sources, consumption of eco-friendly items, and waste recycling (Abid et al., 2022). According to Tariq et al. (2022), technologies are used as resources to promote environmental sustainability. As such, environmental pollution has been levied in economies that embrace them. Green innovations and green technologies are identified among the vital determinants of environmental sustainability and are expected to mitigate the environmental pressure of South Asian countries. Innovations provide access to modern machinery, accelerate economic growth, and improve energy efficiency. Also, as suggested by Khurshid et al. (2022), environmental policies in juxtaposition with innovative technologies are effective in levitating environmental degradation and enhancing environmental quality. Considering the African perspective, Obobisa et al. (2022) divulged that green innovations can help the underlying countries tackle the climate change issue. Likewise Sakariyahu et al. (2023), proved that technological innovations are effective in alleviating the environmental pressure of some African countries as it stimulates the development of low-carbon technologies.

Lastly, a summary of these extant empirical studies on the nexus of financial globalization, innovative technologies, and natural resources with environmental indicators has been provided in Table 1 for a holistic understanding of the current state of the literature.

2.3. Existing literature gaps and merit of the study

From the literature, we observed that certain efforts have been made toward environmental concerns. Nonetheless, the literature on the link between financial globalization, green innovations, and environmental sustainability yielded contrasting outcomes. The mixed discoveries might be a result of the differences in geographical locations, study variables, period, econometric approaches, and the study sample just to mention a few. This signposts that, the debate on the nexus amidst the series is inconclusive and warrants further interrogations. Besides, it can be deduced from the literature reviews that, prior explorations in their attempt to study the connection amidst financial globalization, green innovations, and environmental quality only examined the direct effects without taking into consideration the indirect effects. This study fills this gap by examining the moderating effects of green innovations in the link between financial globalization and environmental sustainability. In addition, preceding investigations also failed to examine the quadratic association between financial globalization and ecological sustainability. This study patches that void by examining the nonlinear connection between financial globalization and environmental quality in West Africa. Finally, all the analyses were conducted within an EKC framework because understanding how different economic growth stages impacted the regions' environmental sustainability could help unravel the potential trade-offs and implementation measures that could drive the ecological quality targets of the countries. As much as we are aware, this innovative approach has not been adopted by prior explorations, especially for the specific case of this rapidly emerging region.

3. Methodology

3.1. Data source

In examining the links amidst the series, panel data of 13 West African economies between 1990 and 2019 is used. The timeframe used for the analysis is dictated by data availability and the countries covered are listed in Table 2. Specifically, data on the ecological footprints (EFP) of the countries is available until 2022, while that on financial globalization (FG) and green innovations (GI) are available until 2020 and 2019 respectively. Also, data on income is available to 2022 while that on natural resource rents (NRR) is available to 2021. However, data on most of the series are not available for periods below 1990. Therefore, using 1990 as the start date and 2019 as the end date, the period 1990–2019 is appropriate for the study because all the variables have significant data over that time frame. The analyzed nations and other details on the variables are shown in Table 2.

Table 1
Summary of recent studies.

Study	Region/country	Methodology	Variables	Results	Abbreviations	
Ulucak et al. (2020)	Emerging economies	Panel DOLS and panel ARDL	EF, GDP, FG, POP	FG (−), no evidence on EKC	DOLS – dynamic ordinary least squares	EGL – economic globalization
Miao et al. (2022)	Newly industrialized countries	MMQR	EF, GDP, FG, NR, RE	FG (−), EKC validated	ARDL – autoregressive distributed lag	GI – green innovations
Farouq et al. (2021)	Sub Saharan African countries	Panel ARDL	CO, GDP, FG, RE	FG (−), EKC validated	EF – ecological footprint	LP – logistics performance index
Sadiq et al. (2022)	Brazil, Russia, India, China, South Africa	Panel ARDL	CO, GDP, FG, RE, NE, ED, HDI	FG (+)	FG – financial globalization	ER – environmental regulation
Wang et al. (2022)	One Belt One Road	GMM	GHG, HDI, GF, GDP. FDI, FD, TO, RD	FG (+)	MMQR – Method of Moments Quantile regression	EE – energy efficiency
Chen et al. (2023)	Brazil, Russia, India, China, South Africa	Panel ARDL	GG, HDI, GS,	FG (+)	NR – natural resources	ENP – environmental policy
Shahzad et al. (2022)	China	VAR	EF, FG, TG, ECI, CO	FG (+)	RE – renewable energy	INS – institutions quality
Damrah et al. (2022b)	Oil exporting countries	MMQR	CI, HDI, POP, FF, ICT	ICT (−)	CO – carbon dioxide emissions	GF – green finance
Wan et al. (2022)	Emerging economies	MMQR	CO, LP, GI, RE, EGL	GI (−)	NE – nuclear energy	GDP – gross domestic product
Wahab et al. (2021)	Canada, France, Germany, Italy, Japan, United Kingdom, United States	Panel ARDL	CO, GDP, TO, ICT	ICT (−)	ED – external debt	POP – population
Chang et al. (2023)	China	GMM	CO, ER, FDI, POP, GI	GI (−)	HDI – human development index	
Wen et al., 2022	African countries	ARDL	CO, FDI, GDP, TO, POP, RE, FF, ICT	ICT (−)	FDI – foreign direct investment	
Abid et al. (2022)	Leading economies	GMM	CO, FD, GI, TR, FF, GDP, FDI, POP, ICT	GI (−)	FD – financial development	
Tariq et al. (2022)	South Asian countries	Panel DOLS	GHG, GDP, RE, EE, FDI, TO, GI	GI (−)	TO – trade openness	
Khurshid et al. (2022)	European countries	Panel ARDL	CO, GI, TRD, ENP	GI (−)	GHG – greenhouse gasses	
Obobisa et al. (2022)	African countries	Panel ARDL	CO, GI, INS, GDP, RE, FF	GI (−)	GMM – generalized method of moments	
Ahmad and Satrovic (2023b)	Organization for Economic Co-operation and Development	MMQR	CI, GDP, GI, RE, FD, NR	NR (+)	VAR – Vector Autoregressive	
Hussain et al. (2022)	Emerging economies	Panel DOLS and panel ARDL	EF, GDP, NR, POP, ENP	NR (+)	TG – Trade globalization	
Kwakwa et al. (2020)	Ghana	ARDL	CO, GDP, POP, TO, NR	NR (+)	TRD – Trademarks	
Aladejare (2022)	African countries	Panel-corrected standard error	CO, NR, TO, HDI, GDP, POP	NR (+)	ECI – Economic complexity index	
Ganda (2022)	Brazil, Russia, India, China, South Africa	Panel-corrected standard error	CO, FD, GDP, NR, FF, TO, FDI, HDI, ICT	NR (+)	CI – carbon intensity	
Cai et al. (2023)	China	DOLS	CO, GDP, ICT, NR	NR (+)	FF – fossil fuels energy consumption	
Hayat et al. (2023)	Organization for Economic Co-operation and Development	MMQR	CO, NR, RE, TO, GDP	NR (−)	ICT – information and communication technology	

Table 2
Data description and measurement units.

Variable	Symbol	Measurement	Source
Ecological footprint	EFP	Global hectare of land	Global Footprint Network (GFN) (https://www.footprintnetwork.org/)
Financial globalization	FG	Financial globalization index	Gygli et al. (2019)
Green innovations	GI	Patents on environment-related technologies (% of total patents on technologies)	Organization for Economic Co-operation and Development (https://data.oecd.org/envpolicy/patents-on-environment-technologies.htm)
Income	Y	GDP (Constant 2015 US$)	World Development Indicators (WDI) (https://databank.worldbank.org/source/world-development-indicators)
Income square	Y^2	Square of GDP	Authors computation
Natural resource rent	NRR	Total natural resources rents (percentage of GDP)	World Development Indicators (https://databank.worldbank.org/source/world-development-indicators)
Financial globalization square	FG^2	Square of financial globalization index	Authors computation

Sample countries: Benin, Burkina-Faso, Cote D'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Mali, Niger, Nigeria, Senegal, Sierra Leone, Togo.

3.2. Model specification and theoretical underpinning

Anthropogenic human activities have been confirmed by many scholars as the key drivers of global warming (Li et al., 2022). Greenhouse gases, especially CO_2 and other pollutant emissions, are the main drivers of this ecological menace. To help mitigate this challenge and attain the sustainable development goals (SDGs) of the United Nations (particularly, SDG 3, SDG 13, SDG 7, SDG 11, SDG 8, SDG 15, and SDG 12, SDG 14), a study on the association between financial globalization and environmental degradation in West Africa, accounting for the role of green innovations is deemed appropriate.

The theoretical underpinning for this study relies on the understating of the ecological modernization theory in connection with the famous EKC conjecture. To begin with, financial globalization is viewed as a key policy factor that affects ecological quality. The innovative study of Islam et al. (2013) is adopted to explain this association. Initially, the energy generation phase was dominated by nonrenewable sources. Since energy is a key component of production, boosting economic growth requires the financialization of nonrenewable energy sources. This implies economy of scale was attained by using the financial system to mobilize funds for the acquisition of production factors for energy generation. However, fostering the energy production process had adverse environmental externalities because it degraded the ecosystem. At that stage, financial globalization had a scale effect on the ecology.

Moreover, the continuous exploitation of natural resources harmed the trajectory of development, demonstrating the unsustainable nature of the scale effect. But as globalization intensified, the composition of production began to change towards an ecologically friendly state through resource reallocation. At that stage, financial globalization had a composition effect on the environment. According to Shahbaz et al. (2022), financialization influenced energy generation in both the high and low energy-intensive sectors. As a result, it was impossible to quantify the compositional impact of financialization, because the rise and contraction of each sector had varying effects on environmental quality. Besides, cost competitiveness and further specialization in trade activities mitigated the cost of eco-friendly technologies. Thus, financial mobilization for energy production led to the generation of clean energy, and the harmful environmental externalities caused by the current energy generation process were being internalized through advancements in ecological sustainability. At this stage, financial globalization had a technique effect on the environment.

In this regard, the ecological modernization theory posits that technological advancements and social change could be embraced to alleviate environmental problems and promote sustainable development. According to the theory, continued economic growth should be viewed as the path to finding solutions to lessen climate change and other ecological issues. Its fundamental tenet is the idea that industrialized nations can adequately address environmental issues because continuous economic expansion slows down environmental degradation via technological and institutional changes.

Proponents of the ecological modernization theory contend that democracy, the state, and the market may be restructured to address concerns related to ecological sustainability (Howes et al., 2010). Hence, governments should provide an environment that encourages innovation and the adoption of technological advancements that are more effective. To the theory, individual nations will be able to solve environmental damage through technological improvements, because innovative technologies are the solutions to the prevailing ecological issues.

We build our analysis on the environmental Kuznets curve framework of Grossman and Krueger (1991). According to this hypothesis, pollution levels rise, and environmental quality deteriorates at the early stages of economic development. However, the trend reverses at a certain threshold level of per capita income, such that as income levels rise, economic advancement leads to ecological gains. This means environmental impacts and per capita income are flanked by an inverted U-shaped association. In examining the connection between financial globalization and environmental sustainability, while accounting for the role of green innovations, the following baseline model in an environmental Kuznets curve framework was developed for estimation;

$$\ln EFP_{it} = \alpha_0 + \beta_1 \ln FG_{it} + \beta_2 \ln GI_{it} + \beta_3 \ln Y_{it} + \beta_4 \ln Y^2{}_{it} + \beta_5 \ln NRR_{it} + \mu_{it} \quad (1)$$

where ecological footprint (EFP) is the endogenous variable representing environmental degradation and financial globalization (FG) and green innovations (GI) are the main exogenous variables of concern. Income (Y) and income squared (Y^2) are incorporated into the framework to investigate the environmental Kuznets curve assumption, while natural resource rent (NRR) is used as a control variable to lessen the implications of model specification bias. Also, α_0 is the constant term; β_1, β_2, β_3, β_4, and β_5 are the corresponding parameters of the predictors; i denotes the cross-sections, t is the timeframe, and μ is the residual term.

All the variables in Eq. (1) are in their log forms to help reduce heteroscedasticity and data fluctuations. In line with Lind and Mehlum (2010), we differentiate Eq. (1) with respect to Y to obtain the threshold level as;

$$\frac{\partial \text{lnEFP}_{it}}{\partial \text{lnY}_{it}} = \beta_3 + 2\beta_4 \text{lnY}_{it} \tag{1a}$$

Setting Eq. (1a) to zero, the turning point of the variable is computed as;

$$\text{lnY}_{it} = \frac{-\beta_3}{2\beta_4} \tag{1b}$$

Unlike the regularly used CO_2 emissions, ecological footprints are viewed as the best measure of environmental degradation, because it is a broader and complete assessment of human-related strain on the ecology (Satrovic and Adedoyin, 2022). Carbon emissions, cropland, fishing grounds, grazing land, forest products, and built-up land are the six constituents of ecological footprints, making it an all-encompassing measure of environmental degradation (Yang et al., 2022). Therefore, following Sun et al. (2023a), we use ecological footprints as a measure of environmental degradation in our exploration.

Besides, financial globalization can influence environmental degradation in diverse ways. First, according to the scale effect, financial globalization damages the environment by supporting investments in industrial and other economic activities that are not environmentally friendly. Also, via the technique and composition effects, financial globalization helps nations to fund investments in green energies, technological innovations, and energy-saving initiatives that promote a sustainable environment. Based on the above, the coefficient of financial globalization could be positive $\left(\beta_1 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnFG}_{it}} > 0\right)$ or negative $\left(\beta_1 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnFG}_{it}} < 0\right)$, validating the exploration of Adebayo et al. (2023).

Moreover, green technological innovations lower pollution by cutting the consumption of dirty fuels (Wan et al., 2022); and increasing the share of ecologically friendly resources, and waste recycling (Abid et al., 2022). Innovations include effective business practices, new production techniques, and products and services that benefit individuals and the environment (Ali et al., 2022). According to Damrah et al. (2022b), these factors improve society and have a favorable impact on businesses as a whole. Innovative technologies also improve energy efficiency, which helps to mitigate ecological damage (Wen et al., 2022). By providing access to modern machinery, green innovations help to lower environmental pollution, and eventually accelerate economic progress. Based on the above, we project the coefficient of the variable to be negative $\left(\beta_2 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnGI}_{it}} < 0\right)$ collaborating with the study of JinRu and Qamruzzaman (2022).

According to Verbič et al. (2022), a major driver of ecological sustainability in economies is income. The environmental Kuznets curve conjuncture proposes the association between income and environmental deterioration to be inverted U-shaped. This means, initially, the rise in income leads to a rise in ecological degradation, but, after attaining a certain threshold point, any further rise in income helps to minimize pollution in the environment (Grossman and Krueger, 1991). Thus, at higher levels of income, the development of technologies and strict environmental regulations emerge, thereby promoting environmental quality (Verbič et al., 2022). Based on the above, we expect the coefficient of income to be positive $\left(\beta_3 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnY}_{it}} > 0\right)$ and income squared to be negative $\left(\beta_4 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnY}^2_{it}} < 0\right)$, validating the environmental Kuznets curve hypothesis (Jena et al., 2022).

Besides, there is ambiguity amidst natural resources and ecological quality. On one hand, increased natural resource extraction puts much pressure on the environment, which subsequently increases ecological degradation. According to Kwakwa et al. (2020), too much dependence on resources could damage the ecosystem because of the energies used in the extraction and disposition of the waste. On the other hand, natural resource abundance draws foreign investments that are related to technologies that improve the ecology (Shahabadi and Feyziand, 2016). Based on the above, we expect the coefficient of natural resources to be positive $\left(\beta_5 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnNR}_{it}} > 0\right)$ or negative $\left(\beta_5 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnNR}_{it}} < 0\right)$ validating the investigation of Nathaniel (2021).

To examine the moderation role of green innovations in the link between financial globalization and environmental pollution, the baseline framework is augmented with the interactive term of green innovations and financial globalization $(\text{FG} * \text{GI})$ resulting in the ensuing framework;

$$\begin{aligned}\text{lnEFP}_{it} = {} & \alpha_0 + \beta_1 \text{lnFG}_{it} + \beta_2 \text{lnGI}_{it} + \beta_3 \text{lnY}_{it} + \beta_4 \text{lnY}^2{}_{it} \\ & + \beta_5 \text{lnNRR}_{it} + \delta_1 (\text{lnGI}_{it} * \text{lnFG}_{it}) + \mu_{it}\end{aligned} \tag{2}$$

where β_1, β_2, β_3, β_4, and β_5 are the coefficients of lnFG, lnGI, lnY, lnY^2, and lnNRR respectively, and δ_1 is the parameter of the interactive term $(\text{GI} * \text{FG})$. The sign of δ_1 is expected to be positive $(\delta_1 > 0)$ if the interaction between green innovations and financial globalization is damaging to ecological quality. Contrastingly, if the interaction between green innovations and financial globalization reduces ecological degradation, then the parameter of the interactive term can be negative $(\delta_1 < 0)$.

Lastly, to examine a possible non-linear association between financial globalization and environmental pollution, the square term of financial globalization (FG^2) is incorporated into the baseline framework. Many extant studies provide evidence for the detrimental effects of globalization. However, we argued that while this may be the case, the possibility of an otherwise case should not be discarded. It will be laudable to examine any possible non-linear nexus. The square of financial globalization is the level financially globalized activities could rise to before the turning point could occur. Thus, we seek to examine whether higher levels of financial globalization could lead to increased demand for ecological protection. This could serve as a base for designing environmental standards capable of mitigating pollution in the region. The resulting model after including the square term of financial globalization becomes;

$$\begin{aligned}\text{lnEFP}_{it} = {} & \alpha_0 + \beta_1 \text{lnFG}_{it} + \beta_2 \text{lnGI}_{it} + \beta_3 \text{lnY}_{it} + \beta_4 \text{lnY}^2{}_{it} \\ & + \beta_5 \text{lnNRR}_{it} + \pi_1 \text{lnFG}^2{}_{it} + \mu_{it}\end{aligned} \tag{3}$$

where FG^2 denotes the square of financial globalization, and β_1, β_2, β_3, β_4, and β_5 are the coefficients of lnFG, lnGI, lnY, lnY^2, and lnNRR correspondingly, and π_1 is the coefficient of FG^2. The association between financial globalization and ecological footprints is nonlinear if elasticity coefficients β_1 and π_1 have different signs and are statistically significant. An inverted U-shaped relationship is discovered if β_1 is greater than zero $\left(\beta_1 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnFG}_{it}} > 0\right)$ and π_1 is less than zero $\left(\pi_1 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnFG}^2{}_{it}} < 0\right)$. On the other hand, a U-shaped relationship is established if β_1 is less than zero $\left(\beta_1 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnFG}_{it}} < 0\right)$ and π_1 is greater than zero $\left(\pi_1 = \frac{\partial \text{lnEFP}_{it}}{\partial \text{lnFG}^2{}_{it}} > 0\right)$. Differentiating Eq. (3) concerning FG, the threshold level is computed as in Lind and Mehlum (2010) as;

$$\frac{\partial \text{lnEFP}_{it}}{\partial \text{lnFG}_{it}} = \beta_1 + 2\pi_1 \text{lnFG}_{it} \tag{3a}$$

Setting the partial derivatives to zero, the turning point of the variable could be computed as;

$$\ln \text{FG}_{it} = \frac{-\beta_1}{2\pi_1} \tag{3b}$$

3.3. Econometric techniques

3.3.1. Cross-sectional dependence tests

Cross-sectional dependence (CD) may occur due to the influence of unobserved common factors shared by all panel units (Henningsen and Henningsen, 2019). The failure to account for CD in panel data analysis may result in biased and inconsistent estimates that might lead to wrong conclusions (Pesaran, 2015). Therefore, as a first step, the Pesaran (2015) CD is performed to determine dependencies or otherwise in the panel. In a Monte Carlo simulation, it was demonstrated that this CD test has the correct size for all combinations of N and T, regardless of whether the panel contains lagged values of the response variable, as long as there are no significant asymmetries in the error distribution (Pesaran, 2015). This test assumes that the null of weak dependence is more fitting than the null of independence which could be quite restrictive for large panels (Pesaran, 2015). The implicit null of this test is given by $0 \le \alpha < (2 - \epsilon)/4$ where α represents the exponent of the CD expressed as.

$$\bar{\rho}_N = [2/(N(N-1))]\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij} = O\left(N^{2\alpha-2}\right) \tag{4}$$

where α estimates the degree of CD among the error terms and ρ_{ij} is the population correlation coefficient of β_{it} and β_{jt}. To test the robustness of the Pesaran (2015) test, the Pesaran scaled Lagrange Multiplier test, the Breusch-Pagan Lagrange Multiplier test, and the Bias-adjusted Lagrange Multiplier test are also conducted.

3.4. Slope heterogeneity test

The analyzed series vary across the cross-sectional units. These variations may cause heterogeneity in the slope coefficients. According to Kong et al. (2022) and Obobisa et al. (2022), failure to account for heterogeneity in panel data analysis may lead to biased estimates and conclusions. Therefore, as a second step, the Pesaran and Yamagata (2008) test is performed to determine whether the slope coefficients are heterogeneous or homogeneous. This test is beneficial because it is robust to CD and performs well in large N and T panels (Bersvendsen and Ditzen, 2020). The Pesaran and Yamagata (2008) test predicts the delta tilde ($\widetilde{\Delta}$) and the adjusted delta tilde ($\widetilde{\Delta}_{adj}$) tests expressed as.

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S} - k}{\sqrt{2k}}\right) \tag{5}$$

$$\widetilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}S - E(\widetilde{z}_{iT})}{\sqrt{Var(\widetilde{z}_{iT})}}\right) \tag{6}$$

where $\widetilde{\Delta}$ is the Swamy (1970) test and $\widetilde{\Delta}_{adj}$ is its adjusted version. This test assumes that $\xi_{i,t}$ and $\xi_{j,s}$ are independently distributed for $i \neq j$ and/or $t \neq s$, but allows for heterogeneous variance (Bersvendsen and Ditzen, 2020). The null hypothesis of homogeneity against the alternative hypothesis of heterogeneity are respectively expressed as:

$$H_0: \ \beta_{2i} = \beta_2 \text{ for some } i \tag{7}$$

$$H_A: \ \beta_{2i} \neq \beta_2 \text{ for some } i \neq j \tag{8}$$

3.5. Unit root tests

The integration order of series is essential because it determines the ensuing econometric methods to be employed. Therefore, as a third step, the cross-sectionally augmented ADF (CADF) and the cross-sectionally augmented IPS (CIPS) tests are engaged to examine the unit root properties of the variables, aligning with the study of Habiba et al. (2022). Under the CADF technique, the standard ADF regressions are augmented with the cross-sectional averages of the lagged levels and first-differences of the individual series to obtain individual CADF statistics and for their simple averages known as the CIPS (Pesaran, 2007). According to Pesaran (2007), the proposed tests have the advantage of being simple and intuitive. A Monte Carlo simulation conducted on the tests confirmed them to have a satisfactory size and power even in relatively small values of N and T (Pesaran, 2007). The CADF test is specified as:

$$\Delta y_{it} = a_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + \sum_{j=0}^{p} d_{ij}\overline{\Delta y}_{t-j} + \sum_{j=1}^{p}\delta_{ij}\Delta y_{i,t-j} + e_{it} \tag{9}$$

where $\bar{y}_{t-j}$ and $\Delta\bar{y}_{t-j}$ denote cross-sectional means. Averaging the above test results in the CIPS test expressed as:

$$\text{CIPS} = N^{-1}\sum_{i=1}^{N}\text{CADF}_i \tag{10}$$

where CADF_i is the CADF test statistic of the ith cross-sectional unit. According to Pesaran (2007), the asymptotic null distribution of the individual CADF and CIPS are examined as $N \to \infty$ followed by $T \to \infty$ as well as both N and T tending to ∞ such that $N/T \to$k where k is a fixed finite non-zero positive constant. Because the CADF and the CIPS tests do not control for structural breaks, the Bai and Carrion-I-Silvestre (2009) test which is efficient for structural breaks is also performed.

3.6. Cointegration tests

The test for cointegration is essential because it serves as the basis for the estimation of the long-run elasticities of predictors. In the presence of CD, the adoption of conventional cointegration tests for panel regression analysis is inappropriate because those tests are not robust to cross-sectional correlations. Therefore, following Ehigiamusoe et al. (2022), the Westerlund (2007) cointegration test is conducted to check the cointegration features of the series at the fourth stage of the analysis. This test presents four novel panel tests for the null hypothesis of no cointegration. The tests do not impose any common factor limitation because they are based on structural dynamics instead of residual dynamics (Westerlund, 2007). The suggested tests are panel expansions of Banerjee et al.'s (1998) test for time series data. Hence, in a conditional error correction model, the tests are intended to determine whether the error correction term equals zero (Westerlund, 2007). Failure to confirm the null hypothesis of error correction implies the failure to validate the null hypothesis of no cointegration (Westerlund, 2007). According to Boukhelkhal (2022), this test is advantageous because it controls for dependencies in cross-sectional units. The test is expressed as:

$$\Delta z_{it} = \delta_i' d_i + \theta_i\left(z_{i(t-1)} + \pi_i'\right) + \sum_{j=1}^{m}\theta_i\Delta z_{i(t-1)} + \sum_{j=1}^{m}\varphi_i\Delta y_{i(1-j)} + \omega_{it} \tag{11}$$

where θ_i measures the speed of adjustment to the equilibrium association. The Westerlund's (2007) test consists of two group mean statistics and two panel mean statistics expressed as:

$$G_\tau = \frac{1}{N}\sum_{i=1}^{N}\frac{\theta_i}{SE\left(\widehat{\theta}_i\right)} \tag{12}$$

$$G_\alpha = \frac{1}{N}\sum_{i=1}^{N}\frac{T\theta_i}{\theta_i'(1)} \tag{13}$$

$$P_\tau = \frac{\widehat{\theta}_i}{SE\left(\widehat{\theta}_i\right)} \tag{14}$$

$$P_\alpha = T\widehat{\theta}_i \tag{15}$$

where G_τ and G_α denote group mean statistics and P_τ and P_α represent panel mean statistics. It is worthwhile to account for structural breaks in our analysis because failure to do so could result in biased estimates and inferences. Hence, the Banerjee and Carrion-i-Silvestre (2017) test, which is robust to structural breaks is also performed.

3.7. Panel regression analysis

The study proceeds to estimate the elasticities of the regressors after the tests for cointegration. Since the panel under consideration is flanked by CD and heterogeneity, the adoption of conventional econometric methods for the parameter estimates is inappropriate (Chudik et al., 2017) because such techniques assume homogeneity and cross-sectional independence. However, according to Le and Sarkodie (2020), failure to account for the above issues might lead to wrong estimates and conclusions. Hence, following Sun et al. (2022), the cross-sectional autoregressive distributed lag (CS-ARDL) technique is first adopted to examine the coefficients of the determinants. This technique is beneficial because it controls for cross-sectional correlations in error terms (Chudik and Pesaran, 2015), by augmenting the autoregressive distributed lag (ARDL) model with cross-sectional means of both the dependent and independent variables (Chudik et al., 2016). The approach is advantageous because it considers the lagged criterion variable as a weakly exogenous regressor within the error correction process (Sohag et al., 2021). The CS-ARDL technique significantly controls for unobservable factors used in measuring the long-term effects in regression models (Kilinc-Ata et al., 2023). Besides, the estimator accounts for heterogeneity and endogeneity in regression models (Chudik and Pesaran, 2013), and offers valid and reliable outcomes in small-sized datasets (Chen et al., 2022). Following Chudik and Pesaran (2015) and Wen et al. (2022), the study's CS-ARDL specification for the baseline model with augmented lags of the cross-sectional averages to account for CD is specified as:

$$\begin{aligned}\text{lnEFP}_{it} = {} & w_i + \sum_{j=1}^{p_y}\lambda_{ij}\text{lnEFP}_{it-j} + \sum_{j=0}^{p_x}\beta_{1j}\text{lnFG}_{it-j} + \sum_{j=0}^{p_x}\beta_{2j}\text{lnGI}_{it-j} \\ & + \sum_{j=0}^{p_x}\beta_{3j}\text{lnY}_{it-j} + \sum_{j=0}^{p_x}\beta_{4j}\text{lnY}^2{}_{it-j} + \sum_{j=0}^{p_x}\beta_{5j}\text{lnNRR}_{it-j} \\ & + \sum_{j=0}^{p}\gamma_{1j}\overline{\text{lnEFP}}_{t-j} + \sum_{j=0}^{p}\gamma_{2j}\overline{\text{lnFG}}_{t-j} + \sum_{j=0}^{p}\gamma_{3j}\overline{\text{lnGI}}_{t-j} \\ & + \sum_{j=0}^{p}\gamma_{4j}\overline{\text{lnY}}_{t-j} + \sum_{j=0}^{p}\gamma_{5j}\overline{\text{lnY}^2}_{t-j} + \sum_{j=0}^{p}\gamma_{6j}\overline{\text{lnNRR}}_{t-j} + \varepsilon_{it}\end{aligned} \tag{16}$$

where $\overline{\text{lnEFP}}$, $\overline{\text{lnFG}}$, $\overline{\text{lnGI}}$, $\overline{\text{lnY}}$, $\overline{\text{lnY}^2}$, and $\overline{\text{lnNRR}}$ are the cross-sectional means of the endogenous and exogenous series correspondingly. The equations for the interactive and the nonlinear models are shown in Eqs. (A1)–(A2) of the Appendix.

It is essential to examine the robustness of the CS-ARDL results, hence the common correlated effects mean group (CCEMG) technique of Pesaran (2006) and the augmented mean group (AMG) technique of Bond and Eberhardt (2013) are also adopted.

These methods are engaged because they are efficient for panels flanked by heterogeneity and cross-sectional correlations. According to Liddle (2018), the AMG and the CCEMG approaches are suitable for variables with mixed order of integration.

The CCEMG technique does not require the estimation of the number of unobserved factors and permits individual-specific errors and unobserved factors to follow an arbitrary stable process (Pesaran, 2006). The fundamental idea is to employ cross-sectional means to filter the individual-specific regressors. This ensures that, as the cross-section dimension (N) approaches infinity, the differential effects of unobserved common factors are eliminated asymptotically (Pesaran, 2006). The advantage of this technique is that it augments the observed regressors with the cross-sectional averages of the individual-specific regressors (Pesaran, 2006). This helps to control for correlations among the cross-sectional units. Even for very small values of N and T, and with a significant degree of heterogeneity and dynamics, the CCE estimators in a Monte Carlo experiment exhibited good small sample properties (Pesaran, 2006). Following Pesaran (2006), the CCEMG specification with respect to the baseline model is specified as:

$$\begin{aligned}\text{lnEFP}_{it} = {} & \alpha_0 + \beta_1\text{lnFG}_{it} + \beta_2\text{lnGI}_{it} + \beta_3\text{lnY}_{it} + \beta_4\text{lnY}^2{}_{it} \\ & + \beta_5\text{lnNRR}_{it} + \text{k}_1\overline{\text{lnFG}_{it}} + \text{k}_2\overline{\text{lnGI}_{it}} + \text{k}_3\overline{\text{lnY}_{it}} \\ & + \text{k}_4\overline{\text{lnY}^2{}_{it}} + \text{k}_5\overline{\text{lnNRR}_{it}} + \varepsilon_{it}\end{aligned} \tag{17}$$

where $\overline{\text{lnFG}_{it}}$, $\overline{\text{lnGI}_{it}}$, $\overline{\text{lnY}_{it}}$, $\overline{\text{lnY}^2{}_{it}}$, and $\overline{\text{lnNRR}_{it}}$ denote the cross-sectional averages of the individual-specific regressors. The CCEMG specifications for the interactive and the nonlinear models are shown in Eqs. (A3)–(A4) of the Appendix.

Besides, the AMG approach is estimated through two stages. With respect to the baseline model, Eq. (1) is first specified in a T-1 dummies and first differenced form as;

$$\begin{aligned}\Delta\text{lnEFP}_{it} = {} & \alpha_0 + \beta_1\Delta\text{lnFG}_{it} + \beta_2\Delta\text{lnGI}_{it} + \beta_3\Delta\text{lnY}_{it} \\ & + \beta_4\Delta\text{lnY}^2{}_{it} + \beta_5\Delta\text{lnNRR}_{it} + \sum_{t=2}^{T}\varnothing_t(\Delta\text{D}_t) + \varepsilon_{it}\end{aligned} \tag{18}$$

where ΔD_t is the first difference order of $T-1$ dummies, and $\varnothing_t$ is its coefficient. In the second stage, a common dynamic process is formed by transforming $\varnothing_t$ to $\text{P}_t(\varnothing_t = \text{P}_t)$ as;

$$\begin{aligned}\Delta\text{lnEFP}_{it} = {} & \alpha_i + \beta_1\Delta\text{lnFG}_{it} + \beta_2\Delta\text{lnGI}_{it} + \beta_3\Delta\text{lnY}_{it} \\ & + \beta_4\Delta\text{lnY}^2{}_{it} + \beta_5\Delta\text{lnNRR}_{it} + P_t(d_t) + \varepsilon_{it}\end{aligned} \tag{19}$$

$$\begin{aligned}\Delta\text{lnEFP}_{it} - P_t(d_t) = {} & \alpha_i + \beta_1\Delta\text{lnFG}_{it} + \beta_2\Delta\text{lnGI}_{it} + \beta_3\Delta\text{lnY}_{it} \\ & + \beta_4\Delta\text{lnY}^2{}_{it} + \beta_5\Delta\text{lnNRR}_{it} + \varepsilon_{it}\end{aligned} \tag{20}$$

where d_t is the dynamic process. After the transformations, the elasticities of the predictors are respectively computed as;

$$\begin{aligned}& \beta_{1,\text{AMG}} = \frac{1}{\text{N}}\sum_{\text{i}=1}^{\text{N}}\beta_{1\text{i}}, \beta_{2,\text{AMG}} = \frac{1}{\text{N}}\sum_{\text{i}=1}^{\text{N}}\beta_{2\text{i}}, \beta_{3,\text{AMG}} = \frac{\text{I}}{\text{N}}\sum_{\text{i}=1}^{\text{N}}\beta_{3\text{i}}, \\ & \beta_{4,\text{AMG}} = \frac{\text{I}}{\text{N}}\sum_{\text{i}=1}^{\text{N}}\beta_{4\text{i}}, \beta_{5,\text{AMG}} = \frac{\text{I}}{\text{N}}\sum_{\text{i}=1}^{\text{N}}\beta_{5\text{i}},\end{aligned} \tag{21}$$

The AMG model specifications for the interactive and nonlinear models are specified in Eqs. (A5)–(A12) of the Appendix.

3.8. Causality analysis

Finally, the adopted regression techniques do not comment on the causal relationship between variables. Therefore, the Dumitrescu and Hurlin (2012) test is engaged to study the causal connections between the series. This test is beneficial because it controls for heterogeneous slopes as compared to some conventional tests for causality. The Dumitrescu-Hurlin panel causality test is specified as;

$$Y_{it} = w_i + \sum_{m=1}^{M} \alpha_i^{(m)} Y_{it-m} + \sum_{m=1}^{M} \delta_i^{(m)} X_{it-m} + \varepsilon_{it} \tag{22}$$

where Y_{it} and X_{it} are the output and the input variables of country i in time t, w_i is the intercept, M is the lag orders, $\delta_i^{(m)}$ is the regression coefficient, and $\alpha_i^{(m)}$ is the autoregressive coefficient. This test comes out with two statistics expressed as;

$$W_{N,T}^{HNC} = N^{-1} \sum_{i=1}^{N} W_{i,t} \tag{23}$$

$$Z_{N,T}^{HNC} = \frac{\frac{1}{\sqrt{N}}\left[\sum_{i=1}^{N} W_{i,t} - \sum_{i=1}^{N} E(W_{i,t})\right]}{\sqrt{\frac{1}{N}\sum_{i=1}^{N} Var(W_{i,t})}} \tag{24}$$

where $E(W_{i,t})$ and $Var(W_{i,t})$ are respectively the expectations and variances of the $W_{i,t}$ statistic. The hypotheses of the above test are stated as;

$$H_0 = \beta_i = 0 \quad \forall_i = 1, \cdots, N_1$$

$$H_1 = \beta_i = 0 \quad \forall_i = 1, \cdots, N \quad 0 \leq N_1/N < 1 \tag{25}$$

$$H_1 = \beta_i \neq 0 \quad \forall_i = 1, \cdots, N+1, N+2, \cdots, N$$

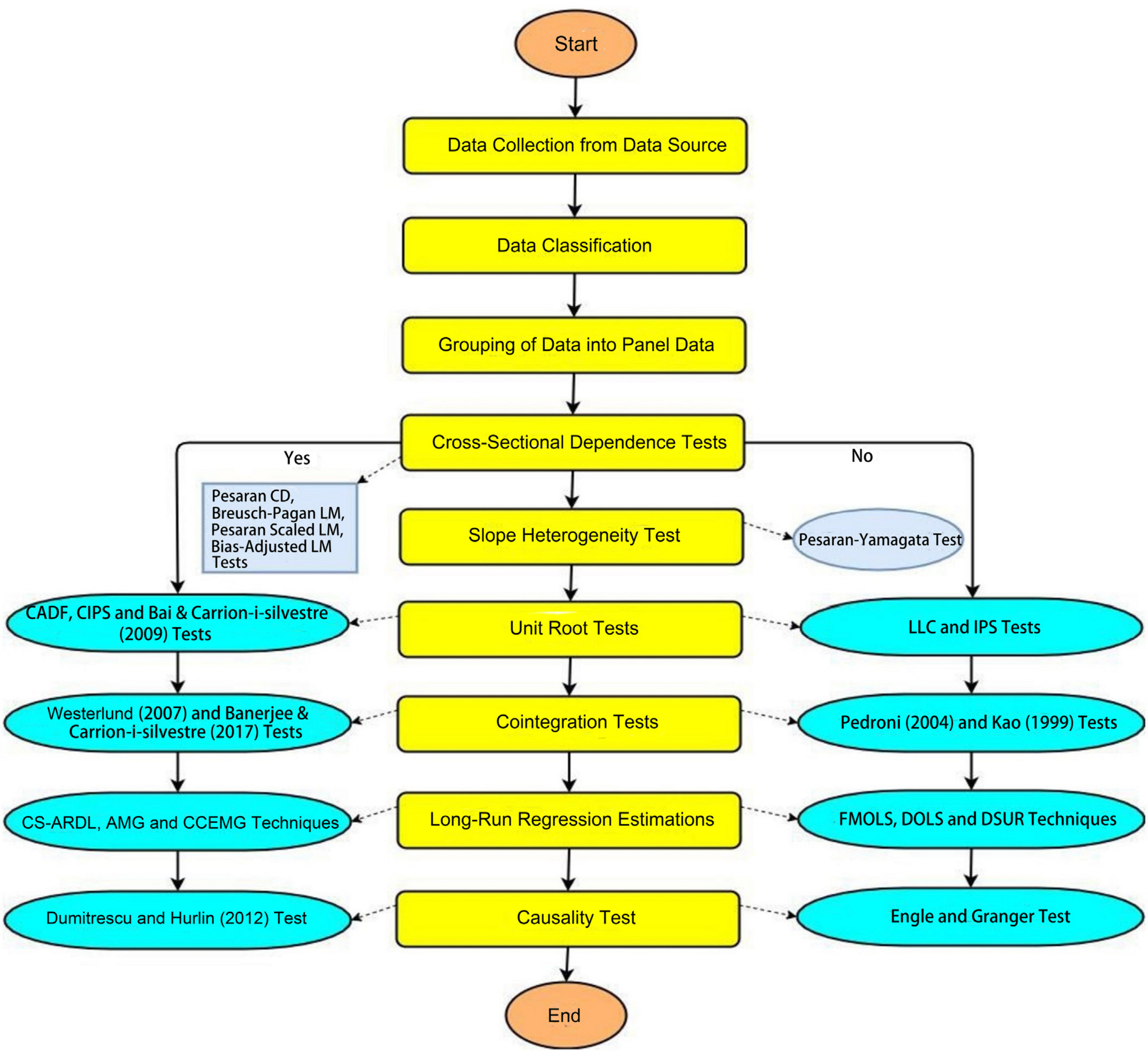

Fig. 4. Overall methodological flowchart.

Table 3
Summary statistics and correlational analysis.

Descriptive statistics					
Statistic	EFP	FG	GI	Y	NRR
Mean	24,668,062	89.48	8.22	2.95E+10	9.41
Median	13,246,093	89.84	8.08	6.13E+09	8.30
Max.	2.09E+08	142.63	23.78	4.93E+11	34.27
Min.	1,101,708	45.00	1.15	6.51E+08	1.72
Std. Dev.	41,231,710	20.00	4.22	7.84E+10	5.86
Skewness	3.16	0.12	2.15	4.11	0.87
Kurtosis	12.25	2.35	6.84	20.25	3.65
Jarque-Bera	1835.19	7.03	14.45	5339.37	50.37
Probability	0.00	0.03	0.03	0.00	0.00
Correlational analysis					
	EFP	FG	GI	Y	NRR
EFP	1.00				
FG	0.56 (0.00)***	1.00			
GI	−0.61 (0.00)***	0.04 (0.25)	1.00		
Y	0.52 (0.00)***	−0.13 (0.06)*	0.27 (0.04)**	1.00	
NRR	0.48 (0.02)**	0.08 (0.17)	0.02 (0.45)	−0.14 (0.05)*	1.00

Note: ***, **, * denote significance at the 1%, 5%, and the 10% levels correspondingly.

The flowchart of the study from data collection to the causality analysis is shown in Fig. 4.

4. Results and discussions

4.1. Descriptive statistics and correlation analysis

The variables' descriptive statistics are shown in Table 3. From Table 3, it can be seen that green innovations have the lowest mean value while income has the highest mean value. Also, income is the most dispersed variable as it records the highest deviation from its mean while green innovations is the least dispersed variable. Furthermore, the skewness results confirm all the series are positively skewed. This means a greater portion of the variables' distribution is found on the left-hand side of the normal curve. Using this, the normal distribution, the kurtosis of the series is platykurtic (flat) relative to the normal except for financial globalization, which is leptokurtic (peaked) relative to the normal distribution. Correlation analyses are finally used to know the degree of linear association between the variables, and also to detect the existence of multicollinearity amidst the series. From the correlation estimates, financial globalization, income, and natural resource rents have a significantly positive association with ecological footprints, but green innovation is significantly negatively related to the ecological footprints of the region. Also, the correlation coefficients between the predictors are less than 0.8. This means, there is no multicollinearity amidst the regressors (Gujarati and Porter, 2012).

4.2. Cross-sectional dependence and heterogeneity analysis

The failure to account for cross-sectional dependence in panel regression analysis could lead to biased estimates and inferences. Hence, we begin the analysis by testing for cross-sectional correlations in the error terms. From the results of the Pesaran (2015) CD test exhibited in Table 4, the null hypothesis of weak cross-sectional dependence cannot be validated. This implies, there is evidence of strong cross-sectional correlations among the residual terms. Also, robustness tests via the Pesaran scaled Lagrange Multiplier test, the Breusch-Pagan Lagrange Multiplier test, and the Bias-adjusted Lagrange Multiplier test confirmed the residual terms to be cross-sectionally correlated. Hence, a major macroeconomic shock in any of the countries will have a spillover effect on the other countries. This finding supports the study of Zhang et al. (2023) for emerging Asian economies.

Table 4
Cross-sectional Dependence (CD) and heterogeneity test results.

CD test	Model 1 (Eq. (1))	Model 2 (Eq. (2))	Model 3 (Eq. (3))
Pesaran CD	15.42(0.00)***	19.15(0.00)***	23.67(0.00)***
Breusch-Pagan LM	155.11(0.00)***	162.82(0.00)***	148.98(0.00)***
Pesaran scaled LM	27.64(0.00)***	33.52(0.00)***	42.86(0.00)***
Bias-adjusted LM	31.03(0.00)***	43.44(0.00)***	55.12(0.00)***
Heterogeneity test			
Delta tilde ($\tilde{\Delta}$)	10.54(0.04)**	13.98(0.00)***	17.17(0.00)***
Adjusted delta tilde ($\tilde{\Delta}_{adj}$)	15.88(0.00)***	19.43(0.00)***	23.85(0.00)***

Note: ***, ** denote significance at the 1% and the 10% levels respectively.

As indicated by Zeraibi et al. (2021), variations in economies might lead to heterogeneity issues in regression analysis. Because the negligence of heterogeneity might result in unreliable estimates and conclusions, it is vital to account for it in our analysis. Hence, the Pesaran and Yamagata (2008) test is performed to determine whether the slope parameters are heterogeneous or homogeneous. Based on the results shown in Table 4, the null hypothesis of homogeneity in the slope parameters cannot be supported. This means the coefficients are heterogeneous in nature. The study of Xu and Khan (2023) supports this finding. The confirmation of heterogeneity and cross-sectional correlations guide the selection of ensuing econometric techniques for the analysis.

4.3. Unit root and cointegration analysis

At the third stage of the analysis, the CADF and the CIPS unit root tests are first performed to assess the integration properties of the variables. From the results displayed in Table 5, the null hypothesis of no stationarity cannot be rejected at levels but is rejected at first difference. This implies the variables are integrated of order I(1). The finding validates the study of Triki et al. (2023) for the Kingdom of Saudi Arabia. Because the above tests are not efficient for structural breaks, the Bai and Carrion-I-Silvestre (2009) is also performed. From the results, the series possesses a first differ-

Table 5
Unit root test results.

CIPS and CADF unit root tests

	CIPS		CADF	
Variable	Levels	1st difference	Levels	1st difference
lnEFP	−2.14	−3.24***	−2.37	−3.57***
lnFG	−1.52	−4.08***	−1.94	−5.11***
lnGI	−1.41	−3.15***	−1.84	−2.77**
lnY	−2.27	−3.46***	−2.31	−4.83***
lnY^2	−1.91	−4.22***	−2.18	−3.75***
lnNRR	−2.23	−3.57***	−2.28	−4.01***
lnGI*lnFG	−1.11	−2.88**	−1.53	−2.94**
lnFG^2	−2.05	−3.64***	−2.17	−4.55***

Bai and Carrion-I-Silvestre (2009) **unit root test**

	Levels			1st difference		
Variable	Z statistic	P_m statistic	P statistic	Z statistic	P_m statistic	P statistic
lnEFP	−0.71	−0.93	41.52	−2.87***	4.58***	88.92***
lnFG	0.36	−0.52	28.11	−1.35*	2.62***	53.65**
lnGI	−0.32	−0.41	26.45	−1.22*	2.56***	50.15**
lnY	−0.58	−0.91	39.73	−2.83***	4.21***	77.41***
lnY^2	−0.44	−0.54	31.05	−1.98**	2.87***	62.31***
lnNRR	−0.54	−0.72	37.32	−2.77***	3.85***	72.15***
lnGI*lnFG	0.42	−0.45	30.41	−1.85**	2.65***	58.03***
lnFG^2	−0.48	−0.63	34.15	−2.62***	3.76***	68.71***

Notes: For Bai and Carrion-I-Silvestre (2009) test, 1%, 5%, and 10% critical values (CV) for Z and P_m statistics are 2.326, 1.645, and 1.282 while the critical values (CV) for P are 56.06, 48.60 and 44.90, separately. Also, ***, **,* denote significance at the 1%, 5% and the 10% levels respectively.

Table 6
Cointegration tests results.

Westerlund (2007) **test**			
Statistic	Model 1	Model 2	Model 3
Gt	−4.83(0.00)***	−5.71(0.00)***	−6.55(0.00)***
Ga	−3.72(0.00)***	−4.85(0.00)***	−5.42(0.00)***
Pt	−2.98(0.04)**	−3.11(0.00)***	−3.43(0.00)***
Pa	−4.56(0.00)***	−2.72(0.03)**	−4.75(0.00)***
Banerjee and Carrion-i-Silvestre (2017) **test**			
Benin	−4.53***	−5.41***	−5.15***
Burkina Faso	−7.57***	−7.73***	−6.78***
Cote D' Ivoire	−6.52***	−5.86***	−7.41***
Gambia	−4.53***	−6.01***	−6.58***
Ghana	−3.88***	−4.42***	−5.52***
Guinea	−7.11***	−6.84***	−7.07***
Guinea-Bissau	−4.38***	−5.52***	−5.82***
Mali	−5.02***	−6.81***	−7.14***
Niger	−6.64***	−7.28***	−6.92***
Nigeria	−2.77**	−4.44***	−2.65**
Senegal	−4.15***	−5.16***	−6.77***
Sierra Leone	−3.74***	−5.88***	−5.98***
Togo	−6.81***	−7.42***	−6.85***

Notes: For the Banerjee and Carrion-i-Silvestre (2017) test, critical values (CV) at 1% and 5% are −2.94 and −2.82 respectively. Also, ***, ** denote significance at the 1% and 5% levels respectively.

Table 7
CS-ARDL estimation results.

Variable	Model 1	Model 2	Model 3
lnFG	0.68(0.00)***	0.74(0.00)***	0.85(0.00)***
lnGI	−1.42(0.00)***	−0.82(0.00)***	−1.67(0.00)***
lnY	0.51(0.00)***	0.42(0.00)***	0.71(0.00)***
lnY^2	−1.04(0.00)***	−0.95(0.00)***	−1.12(0.00)***
lnNRR	0.08(0.02)**	0.17(0.00)**	0.37(0.00)***
lnGI*lnFG	–	−1.22(0.00)***	–
lnFG^2	–	–	−0.88(0.00)***
ECT	−0.73(0.000)***	−0.68(0.000)***	−0.87(0.000)***
F-statistic	121.44(0.00)***	115.35(0.00)***	133.02(0.00)***
R-squared	0.78	0.72	0.83
RMSE	0.04	0.06	0.02
CD-statistic	−3.45(0.32)	−4.26(0.58)	−1.03(0.25)

Notes: lnEFP is the dependent variable; *** and ** denote significance at the 1% and the 5% levels respectively.

enced stationary order aligning the outcomes of the CADF and CIPS tests.

Besides, it is inappropriate to estimate the elasticities of regressors if the variables under investigation do not possess a cointegration association. Therefore, at the fourth stage, the Westerlund (2007) test is first performed to examine the cointegration features of the series. Based on the results shown in Table 6, the null hypothesis of no cointegration cannot be validated. This implies the variables are flanked by a long-run cointegration relationship aligning with the research of Udeagha and Breitenbach (2023) for South Africa. To cater for structural break issues, the Banerjee and Carrion-i-silvestre (2017) test is also applied. The test's outcomes confirm the variables to be cointegrated in the long-term collaborating the Westerlund's (2007) test. Based on these results, we proceed to explore the elasticities of the regressors.

4.4. Regression and causality analysis

Since the stationarity order has been confirmed and the cointegration test yields evidence of the series being materially related in the long term, the elasticities of the regressors are then first estimated via the CS-ARDL regression technique. From the results depicted in Table 7, financial globalization has a significantly positive effect on ecological footprints in all three models. Ceteris paribus, a 1% increase in financial globalization increases ecological footprints by about 0.68%, 0.74%, and 0.85% respectively. Therefore, financial globalization harms the environment of West Africa.

Also, green innovations negatively predict ecological footprints in all the models. All factors held constant, a 1% rise in green innovations mitigates ecological footprints by about 1.42%, 0.82%, and 1.67% correspondingly. Hence, green innovations improve environmental quality in the region.

Moreover, income has a significantly positive influence on ecological footprints, while the square of income negatively predicts ecological footprints in the models respectively. Specifically, a 1% rise in income escalates ecological footprints by about 0.51%, 0.42%, and 0.71% while the square of income reduces ecological footprints by about 1.04%, 0.95%, and 1.12% respectively. This suggests that income and environmental pollution have an inverted U-shaped relationship. Therefore, the environmental Kuznets curve hypothesis holds for the West African region.

Furthermore, natural resource rents have a significantly positive effect on ecological footprints in the models. Precisely, a 1% increase in natural resource rents results in about 0.08%, 0.17%, and 0.37% rise in ecological footprints correspondingly. Therefore, natural resource rents harm environmental quality in West Africa.

In model 2, the interaction between green innovations and financial globalization negatively predicts ecological footprints in the region. Ceteris paribus, a percentage rise in the interactive term leads to about a 1.22% decrease in ecological footprints. Hence, green innovations reduce the harmful effects of financial globalization on the region's environmental pollution.

Also, in model 3, the coefficient of financial globalization squared (FG^2) is negative, while that of financial globalization is positive. This means the relationship between financial globalization and environmental pollution is inverted U-shaped. Therefore, financial globalization has a nonlinear association with environmental deterioration in West Africa. The overall schematic presentation of the CS-ARDL findings is provided in Fig. 5.

4.4.1. Sensitivity analysis

To examine whether the results are consistent across methodologies, the AMG and CCEMG techniques are engaged to estimate the models. Based on the results shown in Table 8, financial globalization increases ecological footprints in all the models. This implies the variable harms ecological quality in the region. Also, green innovations significantly negatively predict ecological

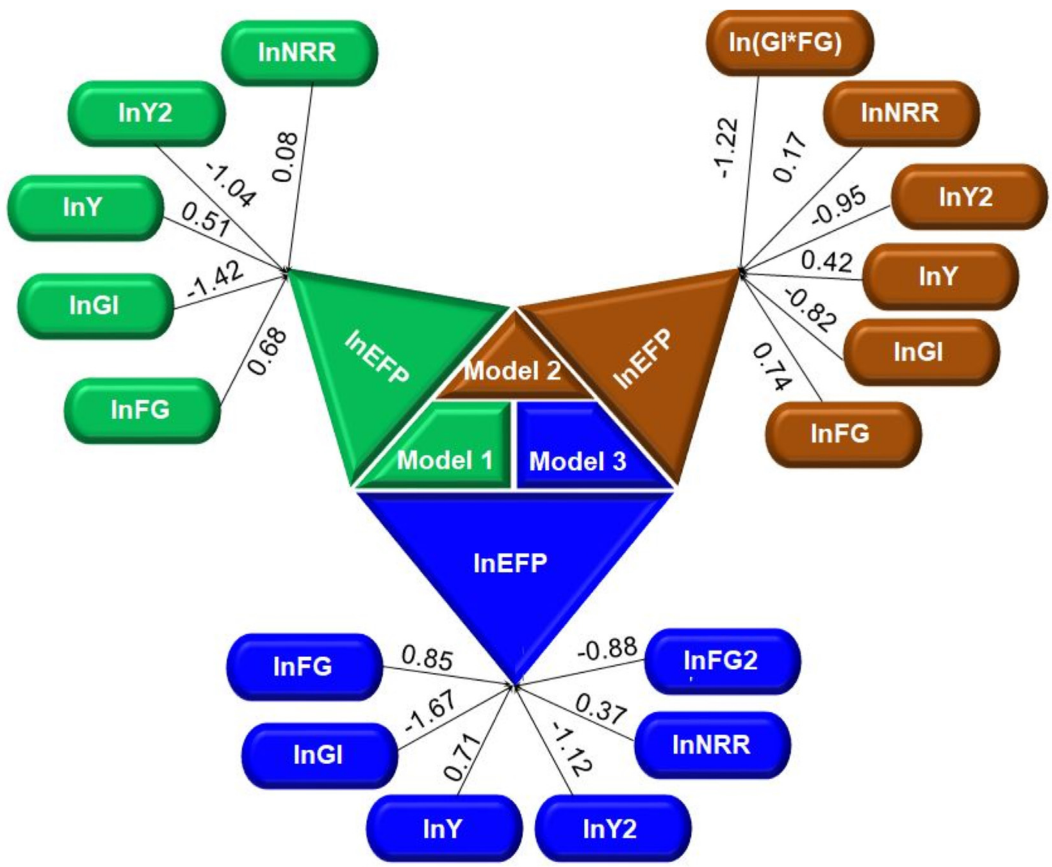

Fig. 5. Schematic presentation of the CS-ARDL simulations.

Table 8
AMG and CCEMG estimation results.

Variable	AMG Model 1	AMG Model 2	AMG Model 3	CCEMG Model 1	CCEMG Model 2	CCEMG Model 3
lnFG	0.43(0.00)***	0.15(0.00)***	0.55(0.00)***	0.04(0.06)*	0.11(0.03)**	0.42(0.00)***
lnGI	−0.78(0.00)***	−0.54(0.00)***	−0.82(0.00)***	−0.51(0.00)***	−0.28(0.00)***	−0.65(0.00)***
lnY	0.24(0.00)***	0.07(0.00)***	0.32(0.00)***	0.14(0.02)**	0.02(0.06)*	0.25(0.00)***
lnY^2	−0.93(0.00)***	−0.45(0.00)***	−0.63(0.00)***	−0.51(0.00)***	−0.21(0.00)***	−0.47(0.00)***
lnNRR	0.04(0.05)*	0.06(0.04)**	0.08(0.02)**	0.03(0.07)*	0.05(0.05)*	0.07(0.03)**
lnGI*lnFG	–	−1.14(0.00)***	–	–	−0.98(0.00)***	–
$lnFG^2$	–	–	−0.45(0.00)***	–	–	−0.32(0.00)***
Wald-stat.	71.23(0.00)***	68.08(0.000)***	75.11(0.00)***	68.04(0.00)***	65.12(0.00)***	70.93(0.00)***
Root MSE	0.04	0.06	0.03	0.05	0.06	0.04
CD-stat.	−4.91(0.57)	−5.14(0.66)	−2.14(0.48)	−5.82(0.68)	−6.91(0.77)	−4.44(0.51)

Note: lnEFP is the response variable. ***, **, * denote significance at the 1%, 5% and the 10% levels respectively.

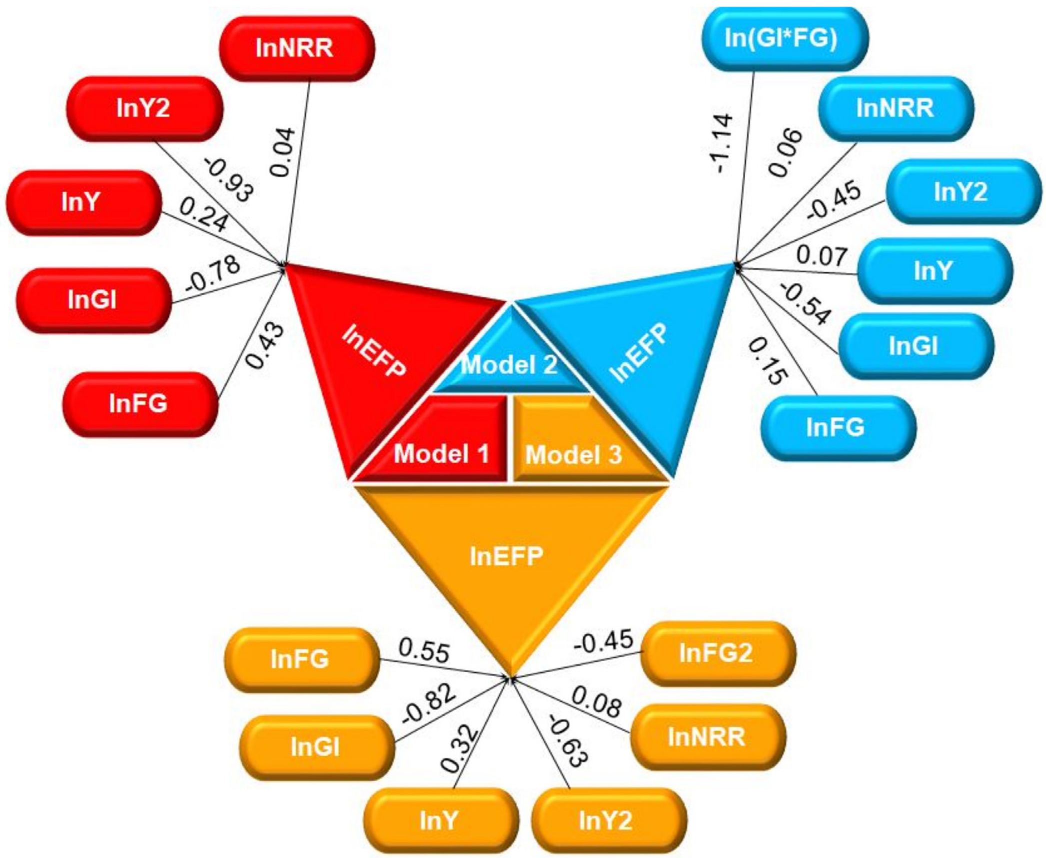

Fig. 6. The schematic presentation of the AMG simulations.

footprints in the region. This suggests that green innovations increase environmental quality in West Africa.

Furthermore, income increases ecological footprints, while the square of income reduces ecological footprints in all the models. This implies income has an inverted U-shaped nexus with ecological degradation. Hence, the environmental Kuznets curve hypothesis is further confirmed for the region.

In model 2, the interaction between green innovations and financial globalization has a materially negative influence on environmental pollution. This implies green innovations minimize the damaging effects of financial globalization on ecological sustainability.

Moreover, the parameter of financial globalization is positive while its square term is negative. This means financial globalization and environmental pollution have an inverted U-shaped relationship in West Africa. Besides, a significantly positive connection between natural resource rents and ecological footprints is detected in all the models. This implies natural resource utilization deteriorates ecological quality in the region.

Though the coefficients of the predictors vary in significance and weight, they are similar in terms of sign. This means our results are valid and reliable. We provided the overall schematic presentation of the AMG and CCEMG simulations in Figs. 6 and 7 respectively.

On the causal relationships amid the series illustrated in Table 9, a bidirectional causality amidst financial globalization and ecological footprints is revealed. Also, income squared has a unidirectional causality with ecological footprints. Similarly, a unidirectional causality occurs between the square of financial globalization and ecological footprints.

Conversely, a bidirectional relationship occurs between green innovations and ecological footprints. Similarly, a feedback causality occurs between the interactive terms of green innovations and financial globalization, and ecological footprints. Finally, income and natural resource rents have a two-way causal relationship with ecological footprints.

5. Further discussion of the results

The CS-ARDL technique is adopted to study the long run impacts of the regressors once the series' cointegration associationhas been established. From the results, financial globalization escalates ecological footprints in all the models. This signifies that the financially globalized activities of the region do not promote ecological sustainability. A potential reason for this outcome is that financial globalization stimulates capital markets, investments, and economic expansion, resulting in increased energy demand and, therefore, more ecological deterioration.

Besides, most resources generated from foreign investments and capital markets are channeled to the development of polluting sectors, thereby worsening the region's environmental improvements. It can also be inferred that financial globalization is not a key mechanism that can promote the composition and technique effects required to phase out the trade-off between economic development and ecological degradation in the bloc.

Furthermore, as the region's demand for goods and services increases, financial globalization helps to develop the production capabilities of businesses, resulting in higher energy utilization and more ecological pollution. This point aligns with the investigation of Sun et al. (2020) who reported that advancements in the

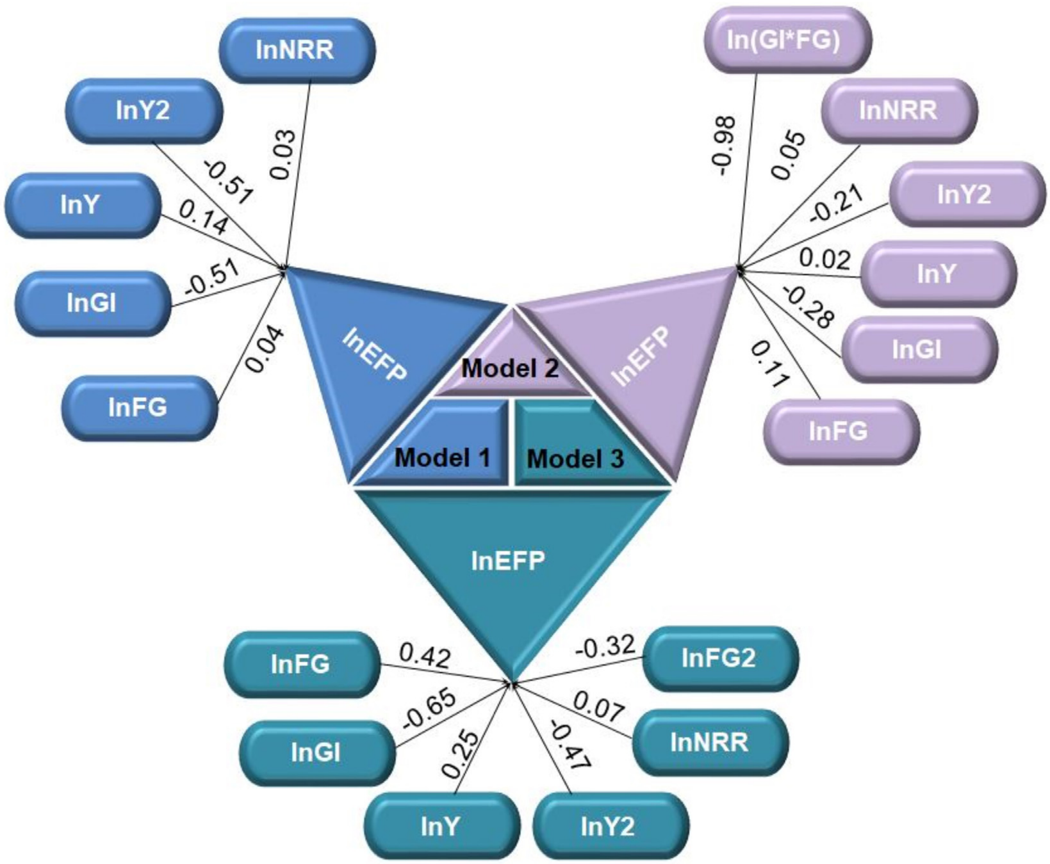

Fig. 7. The schematic presentation of the CCEMG simulations.

Table 9
Dumitrescu-Hurlin panel causality test results.

Null hypothesis	W-stat.	Zbar-stat.	Prob.	Causality flow
lnFG⇏lnEFP	5.14	3.82	0.00***	Bidirectional
lnEFP⇏lnFG	3.68	2.64	0.02**	
lnGI⇏lnEFP	7.94	6.22	0.00***	Bidirectional
lnEFP⇏lnGI	5.24	4.15	0.00***	
lnY⇏lnEFP	4.72	3.51	0.00***	Bidirectional
lnEFP⇏lnY	5.34	4.43	0.00***	
$\ln Y^2$⇏lnEFP	4.61	3.47	0.00***	Unidirectional
lnEFP⇏$\ln Y^2$	1.36	−0.41	0.75	
lnNRR⇏lnEFP	6.43	5.14	0.00***	Bidirectional
lnEFP⇏lnNRR	3.42	2.45	0.03**	
lnGI*lnFG⇏lnEFP	7.21	5.38	0.00***	Bidirectional
lnEFP⇏ lnGI*lnFG	4.17	3.26	0.00***	
$\ln FG^2$⇏lnEFP	7.81	5.45	0.00***	Unidirectional
lnEFP⇏$\ln FG^2$	1.14	−0.56	0.77	

Note: ***, ** denote significance at the 1% and the 5% levels respectively.

financial sector promote pollution. The detrimental effect of financial globalization on ecological quality supports the studies of Adebayo et al. (2022) for China, and Adebayo and Kirikkaleli (2021) for Japan, but conflicts with those of Miao et al. (2022) for industrialized economies, and Ahmad et al. (2021) for G7 nations.

Conversely, green innovations improve environmental quality by reducing ecological footprints in the region. This is not surprising because green innovations promote green energy generation, energy efficiency, and other environmentally friendly initiatives that help to enhance ecological sustainability. The finding supports the investigations of Habiba et al. (2022) for the top twelve emitters, Alola and Onifade (2022) for Finland, Hongqiao et al. (2022) for the United States of America and Bekun et al. (2022) for E7 states, but contrasts that of Cai et al. (2021) who discovered a positive connection between green technology and environmental pollution in the western provinces of China.

Furthermore, income increases ecological footprints in the region. This means rapid economic progress harms the ecology by raising the level of pollution. The risk of possible ecosystem extinction is increased by the acceleration of dirty energy utilization, global warming, financial activities, and ecological degradation brought on by the increase in the level of income. This outcome supports the studies of Xu and Khan (2023) for G7 economies, and Sun et al. (2023b) for China, but varies from that of Gyimah et al. (2023) who discovered a trivial association between economic progress and environmental pollution for Ghana.

Contrariwise, income squared negatively explains ecological footprints in the region. This implies economic growth and pollution in the ecosystem possess an inverted U-shaped association. Hence, the environmental Kuznets curve assumption holds for West Africa. This suggests that pollution levels rise at the early stages of economic advancement but drop at the later stages. Following the approach of Lind and Mehlum (2010), the computed turning point $(-\beta_3/2\beta_4)$ is $[-0.71/2(-1.12)] = 0.317$. Udeagha and Breitenbach (2023) for South Africa, and Jinapor et al. (2023) for some selected nations in Africa support the study's finding, but Magazzino (2015)'s investigation of Israel, Taiwo et al. (2021) investigation of OPEC countries, and Riti and Shu's (2016) research on Nigeria contrast the finding of the study.

Moreover, the coefficient of natural resource rents positively predicts pollution in the models. This means the consumption of natural resources pollutes the region's ecosystem. The discovery is backed by the fact that there are certain major oil-producing economies in the region for example in the case of Nigeria. Besides, most of the nations in the WA region put extreme strain on their natural resources to meet their energy needs. Overexploitation of resources escalates the rate of pollution in the region. Besides, natural resources are used to promote economic development in the region. This means, that as the countries strive for more economic growth, more resources will be exploited, thereby depleting the ecosystem.

Moreover, natural resource activities in the region involve the use of energy-intensive machinery and equipment. This increases the rate of energy consumption (dominated by fossil fuels, coal, and natural gas among others), thereby polluting the ecosystem. Also, forest lands are cleared to pave the way for the extraction of precious minerals from the ground. This harms the environment as neither the trees are replaced, nor the land is reinstated to its original position.

Additionally, because of the strategic placement of economies in the region, the processing and consumption of agricultural resources encourage deforestation, which raises the level of pollution in the bloc. The detrimental effect of natural resources on ecological sustainability aligns with the studies of Zuo et al. (2022) for BRI economies, and Miao et al. (2022) for industrial nations, but contrasts those of Arslan et al. (2022) for China, and Khan et al. (2021) for the United States of America.

Besides, the interactive term between green innovations and financial globalization adversely explains ecological footprints in the region. This means green innovations and financial globalization jointly improve the region's ecological quality. Put differently, green innovations minimize the detrimental effects of financial globalization, by promoting financially globalized initiatives that are friendly to the environment. This finding conflicts with the investigations of Adebayo et al. (2022) for China, and Miao et al. (2022) for newly industrialized economies.

Furthermore, the coefficient of financial globalization squared is negative and that of financial globalization is positive. This means financial globalization and environmental degradation are flanked by an inverted U-shaped relationship. The finding suggests that the damaging effects of financial globalization on the environment are high from the initial stages to a certain level (turning point), after which the environment tends to improve as financial globalization increases. Thus, at the early stages, financial globalization promotes activities that pollute the environment, but at the latter stages, financial globalization stimulates initiatives that enhance environmental quality in the region.

This means nations in the region have attained the level of financial globalization beyond which environmental quality tends to improve. At that point, financial intermediaries factor environmental awareness into their operations by promoting innovative technologies, clean energy utilization, energy efficiency, and research and development activities that are gainful to the environment. These activities help to mitigate environmental pollution in West Africa. In line with Lind and Mehlum (2010), the computed turning point $(-\beta_1/2\pi_1)$ is $[-0.85/2(-0.88)] = 0.483$. Ahmad et al.'s (2021) investigation of G7 nations and Majeed et al.'s (2022) research on BRICS contrasts the above disclosure.

Concerning the causalities, a bidirectional causality between financial globalization and ecological footprints is detected. A probable justification for this finding is that the region's stock markets serve as powerful drivers of economic conditions. This results in the extreme utilization of dirty energies, thereby causing pollution in the bloc. The discovery validates the studies of Cetin et al. (2018) and Shahzad et al. (2017).

Also, causalities from income squared and financial globalization squared to ecological footprints are disclosed. This means ecological degradation is reliant on the above series, but not the opposite. The study of Majeed et al. (2022) contrasts this finding.

Conversely, a bidirectional relationship occurs between financial globalization and ecological footprints. This implies that financially globalized activities promote ecological pollution in the region and vice versa. The finding disagrees with Ahmad et al. (2021) who discovered a one-way causality from financial globalization to ecological pollution. Miao et al.'s (2022) investigation of newly industrialized economies also conflicts with this finding as they disclosed a causation from financial globalization to environmental deterioration.

Likewise, feedback causality occurs between green innovations and ecological footprints. This means the series are interdependent such that, the rise in one variable leads to the rise in the other variable and vice versa. The finding supports that of JinRu and Qamruzzaman (2022) for G7 economies but contrasts that of Tariq et al. (2022) for South Asia.

Moreover, income has a bidirectional relationship with ecological footprints. This implies the region's economic development and environmental degradation are mutually inter-reliant. The discovery supports that of Salman et al. (2022) for ASEAN-4 and Ehigiamusoe et al. (2022) for 31 selected African nations but conflicts with those of Zhang et al. (2023) for emerging Asian economies, and Xu and Khan (2023) for G7 nations.

Similarly, ecological pollution and the interaction between green innovations and financial globalization are bidirectionally related. This means, the rise and fall in the interactive term, results in the rise and fall in ecological deterioration and vice versa. The finding conflicts with the investigations of Adebayo et al. (2022) and Ahmad et al. (2021).

Finally, a feedback causality amidst natural resource rents and ecological pollution is discovered. This implies, that environmental pollution and natural resources caused each other in the region. The research by Wenlong et al. (2023) on the United States of America, and Sarwat et al.'s (2022) investigation on the BRICS economies support this finding, but those of Ahmad et al. (2022) for Chinese provinces, and Awosusi et al. (2022) for Uruguay contrast the discovery of this study.

6. Conclusions and policy implications

Accomplishing the net-zero emission target has become a key agenda of many economies around the globe. Hence, examining the association between financial globalization and environmental sustainability in West Africa, while accounting for the moderating role of green innovations is deemed fitting. In attaining this goal, data from 13 nations in the region over the period 1990 to 2016 is used for the analysis. Due to the implications of heterogeneity and cross-sectional dependence amongst others, vigorous econometric methods are engaged.

From the findings, there is cross-sectional dependence in the residual terms. Also, the slope coefficients are heterogeneous in nature. Besides, the series are first differenced stationary and cointegrated in the long run. The regressors' parameters are estimated through the cross-sectional autoregressive distributed lag (CS-ARDL) technique in conjunction with the common correlated effects mean group (CCEMG) and augmented mean group (AMG) approaches. We observe that financial globalization has an inverted U-shaped relationship with ecological footprints. Thus, environmental pollution rises with an increase in financial globalization to a certain level, after which further increases in financial globalization help to promote ecological quality in the region. Also, green innovations promote environmental benefits by mitigating ecological pollution in the region. Besides, green innovations negatively moderate the impact of financial globalization on the region's ecological footprints. The environmental Kuznets curve conjuncture is also validated by the study. Furthermore, natural resource rents damage the region's ecosystem by promoting more ecological footprints. With respect to the causalities, bidirectional causal relations amidst financial globalization, green innovations, the interaction between financial globalization and green innovations, income, natural resource rents; and ecological footprints are discovered. Also, unidirectional causalities from the square of income and the square of financial globalization to ecological footprints are detected.

Following the findings, financial globalization exhibits a nonlinear detrimental ecological effect, however, green innovations cushion the observed adverse ecological effects of financial globalization in West Africa. We, therefore, recommend that the authorities and policymakers in the West African states should harness the vast possibilities of access to financial flows in the era of globalization by ensuring adequate investment in green and energy-efficient technologies to help boost ecological quality in the region. In this regard, policymakers in the region should set a financial flow-ecological quality balance attainment threshold upon which regular evaluation of the ecological impacts of foreign capital inflow can be assessed to preserve a healthy environment for both the current and future generations. We are also aware of the economic benefits of financial globalization which of course all government in the region seeks to attain, and as such, policymakers must ensure that the nations' ecological sustainability goals are strategically and carefully designed in a way that they do not jeopardize their ability to sustain their economies.

Moreover, given that green innovations negatively predict ecological footprints in the region coupled with its desirable interactive ecological benefits with financial globalization, we further recommend that governments should adopt strategic approaches for increasing research and development (R&D) in environmental-related innovations. Authorities and policymakers in the West African states should leverage financial globalization by providing the enabling environment to attract foreign capital flow to green projects. Alternatively, the governments of these states can also develop workable private–public partnership schemes to support green development projects and boost more funds for initiatives in innovative technologies.

In addition, the environmental Kuznets curve hypothesis is validated for the region. This suggests that if countries in the region promote green technologies and the consumption of clean energies, their future income levels will not be detrimental to environmental sustainability after a certain threshold level. To therefore mitigate the potential negative ecological consequences of economic prosperity, countries in the region must increase investments in clean energies while gradually minimizing the current reliance on non-renewable energy sources. Thus, efforts should be made to improve clean energy generation in the region. In this regard, we recommend that the authorities should leverage the vast natural resources of the region to develop their renewable energy generation capacity and encourage a gradual shift in the current fossil energy resources dependency situation that has been widely reported in the literature amongst countries in the West African region (Onifade and Alola, 2023; Onifade et al., 2023). This will help to lessen the ecological pressure and degradation from resource exploitation among the West African states.

Finally, natural resource rents aggravate ecological footprints in the region. This implies that natural resource exploration activities as well as their utilization undermine ecological quality amongst the West African states. As such, it is very important that the authorities and all stakeholders focus on drafting environmental policies for monitoring and regulating the activities of companies and organizations in the resource extractive industries. This is critical to ensure topmost compliance with best practices for ecologically sustainable resource exploration and utilization activities in the region. In addition, while doing this, the authorities should further encourage a gradual shift away from resource dependency through robust policy initiatives that encourage the development and contributions of other sectors. This diversification away from the focus on the resource extractive industry would not only provide economic benefits but also encourage the attainment of the desired ecological quality in the region.

Though the study achieved its aim, the main identified limitation relates to the restriction of the analytical scope due to the non-availability of data for the other three countries that were left out. However, future studies can be expanded based on the established framework in the current study. While doing so, the theoretical underpinnings can also be broadened to cover other frameworks like the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT). This can further help to determine how the analyzed predictors in the current study explain ecological performance among the West African states in particular, or in other regions across the globe in general.

CRediT authorship contribution statement

Mohammed Musah: Conceptualization, Data curation, Formal analysis, Methodology. **Stephen Taiwo Onifade:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Elma Satrovic:** Data curation, Writing – original draft, Visualization. **Joseph Akwasi Nkyi:** Writing – original draft.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

CS-ARDL model specifications

The study's CS-ARDL models augmented with the lags of the cross-sectional averages of the input and output variables to account for cross-sectional dependence are specified as;

Interactive Model:

$$\ln EFP_{it} = w_i + \sum_{j=1}^{p_y}\lambda_{ij}\ln EFP_{it-j} + \sum_{j=0}^{p_x}\beta_{1j}\ln FG_{it-j} + \sum_{j=0}^{p_x}\beta_{2j}\ln GI_{it-j} + \sum_{j=0}^{p_x}\beta_{3j}\ln Y_{it-j} + \sum_{j=0}^{p_x}\beta_{4j}\ln {Y^2}_{it-j} + \sum_{j=0}^{p_x}\beta_{5j}\ln NRR_{it-j} + \sum_{j=0}^{p_x}\delta_{1j}\ln(FG*GI)_{it-j} + \sum_{j=0}^{p}\gamma_{1j}\overline{\ln EFP}_{t-j} + \sum_{j=0}^{p}\gamma_{2j}\overline{\ln FG}_{t-j} + \sum_{j=0}^{p}\gamma_{3j}\overline{\ln GI}_{t-j} + \sum_{j=0}^{p}\gamma_{4j}\overline{\ln Y}_{t-j} + \sum_{j=0}^{p}\gamma_{5j}\overline{\ln Y^2}_{t-j} + \sum_{j=0}^{p}\gamma_{6j}\overline{\ln NRR}_{t-j} + \sum_{j=0}^{p}\gamma_{7j}\overline{\ln(GI*FG)}_{t-j} + \varepsilon_{it} \quad (A1)$$

Nonlinear Model:

$$\ln EFP_{it} = w_i + \sum_{j=1}^{p_y}\lambda_{ij}\ln EFP_{it-j} + \sum_{j=0}^{p_x}\beta_{1j}\ln FG_{it-j} + \sum_{j=0}^{p_x}\beta_{2j}\ln GI_{it-j} + \sum_{j=0}^{p_x}\beta_{3j}\ln Y_{it-j} + \sum_{j=0}^{p_x}\beta_{4j}\ln {Y^2}_{it-j} + \sum_{j=0}^{p_x}\beta_{5j}\ln NRR_{it-j} + \sum_{j=0}^{p_x}\pi_{1j}\ln {FG^2}_{it-j} + \sum_{j=0}^{p}\gamma_{1j}\overline{\ln EFP}_{t-j} + \sum_{j=0}^{p}\gamma_{2j}\overline{\ln FG}_{t-j} + \sum_{j=0}^{p}\gamma_{3j}\overline{\ln GI}_{t-j} + \sum_{j=0}^{p}\gamma_{4j}\overline{\ln Y}_{t-j} + \sum_{j=0}^{p}\gamma_{5j}\overline{\ln Y^2}_{t-j} + \sum_{j=0}^{p}\gamma_{6j}\overline{\ln NRR}_{t-j} + \sum_{j=0}^{p}\gamma_{7j}\overline{\ln FG^2}_{t-j} + \varepsilon_{it} \quad (A2)$$

where $\overline{\ln EFP}$, $\overline{\ln FG}$, $\overline{\ln GI}$, $\overline{\ln Y}$, $\overline{\ln Y^2}$, $\ln\bar{N}RR$, $\ln(G\bar{I}*FG)$, and $\ln\bar{F}G^2$ are the cross-sectional means of the endogenous and exogenous series correspondingly.

CCEMG model specifications

In the CCEMG procedure, the estimated model is augmented with cross-sectional averages of the regressors to account for cross-sectional correlations. Our study's augmented CCEMG models to control for cross-sectional dependence are specified as;

Interactive Model:

$$\ln EFP_{it} = \alpha_0 + \beta_1\ln FG_{it} + \beta_2\ln GI_{it} + \beta_3\ln Y_{it} + \beta_4\ln {Y^2}_{it} + \beta_5\ln NRR_{it} + \delta_1\ln(GI*FG)_{it} + \psi_1\overline{\ln FG_{it}} + \psi_2\overline{\ln GI_{it}} + \psi_3\overline{\ln Y_{it}} + \psi_4\overline{\ln {Y^2}_{it}} + \psi_5\overline{\ln NRR_{it}} + \psi_6\overline{\ln(GI*FG)_{it}} + \varepsilon_{it} \quad (A3)$$

Nonlinear Model:

$$\ln EFP_{it} = \alpha_0 + \beta_1\ln FG_{it} + \beta_2\ln GI_{it} + \beta_3\ln Y_{it} + \beta_4\ln {Y^2}_{it} + \beta_5\ln NRR_{it} + \pi_1\ln {FG^2}_{it} + \Omega_1\overline{\ln FG_{it}} + \Omega_2\overline{\ln GI_{it}} + \Omega_3\overline{\ln Y_{it}} + \Omega_4\overline{\ln {Y^2}_{it}} + \Omega_5\overline{\ln NRR_{it}} + \Omega_6\overline{\ln {FG^2}_{it}} + \varepsilon_{it} \quad (A4)$$

From the above equations $\overline{\ln FG_{it}}$, $\overline{\ln GI_{it}}$, $\overline{\ln Y_{it}}$, $\overline{\ln {Y^2}_{it}}$, $\overline{\ln NRR_{it}}$, $\overline{\ln(GI*FG)_{it}}$, and $\overline{\ln {FG^2}_{it}}$ denote the cross-sectional averages of the input variables.

AMG model specifications

The AMG approach follows a two-staged process. At the first stage, Eqs. (1), (2), and (3) are specified in a $T-1$ dummies and first differenced form as;

Interactive Model:

$$\Delta\ln EFP_{it} = \alpha_0 + \beta_1\Delta\ln FG_{it} + \beta_2\Delta\ln GI_{it} + \beta_3\Delta\ln Y_{it} + \beta_4\Delta\ln {Y^2}_{it} + \beta_5\Delta\ln NRR_{it} + \delta_1\ln(GI*FG)_{it} + \sum_{t=2}^{T}\varnothing_t(\Delta D_t) + \varepsilon_{it} \quad (A5)$$

Nonlinear Model:

$$\Delta\ln EFP_{it} = \alpha_0 + \beta_1\Delta\ln FG_{it} + \beta_2\Delta\ln GI_{it} + \beta_3\Delta\ln Y_{it} + \beta_4\Delta\ln {Y^2}_{it} + \beta_5\Delta\ln NRR_{it} + \pi_1\ln {FG^2}_{it} + \sum_{t=2}^{T}\varnothing_t(\Delta D_t) + \varepsilon_{it} \quad (A6)$$

From the equations above, ΔD_t is the first difference order of $T-1$ dummies, and $\varnothing_t$ is its coefficient.

In the second stage, common dynamic processes are formed by transforming $\varnothing_t$ to $P_t(\varnothing_t = P_t)$ as;

Interactive Model:

$$\Delta\ln EFP_{it} = \alpha_i + \beta_1\Delta\ln FG_{it} + \beta_2\Delta\ln GI_{it} + \beta_3\Delta\ln Y_{it} + \beta_4\Delta\ln {Y^2}_{it} + \beta_5\Delta\ln NRR_{it} + P_t(d_t) + \delta_1\ln(GI*FG)_{it} + \varepsilon_{it} \quad (A7)$$

$$\Delta\ln EFP_{it} - P_t(d_t) = \alpha_i + \beta_1\Delta\ln FG_{it} + \beta_2\Delta\ln GI_{it} + \beta_3\Delta\ln Y_{it} + \beta_4\Delta\ln {Y^2}_{it} + \beta_5\Delta\ln NRR_{it} + \delta_1\ln(GI*FG)_{it} + \varepsilon_{it} \quad (A8)$$

Nonlinear Model:

$$\Delta\ln EFP_{it} = \alpha_i + \beta_1\Delta\ln FG_{it} + \beta_2\Delta\ln GI_{it} + \beta_3\Delta\ln Y_{it} + \beta_4\Delta\ln {Y^2}_{it} + \beta_5\Delta\ln NRR_{it} + P_t(d_t) + \pi_1\ln {FG^2}_{it} + \varepsilon_{it} \quad (A9)$$

$$\Delta\ln EFP_{it} - P_t(d_t) = \alpha_i + \beta_1\Delta\ln FG_{it} + \beta_2\Delta\ln GI_{it} + \beta_3\Delta\ln Y_{it} + \beta_4\Delta\ln {Y^2}_{it} + \beta_5\Delta\ln NRR_{it} + \pi_1\ln {FG^2}_{it} + \varepsilon_{it} \quad (A10)$$

where d_t is the dynamic process.

After the transformations, the elasticities of the predictors are respectively computed as;

Interactive Model:

$$\beta_{1,AMG} = \frac{1}{N}\sum_{i=1}^{N}\beta_{1i}, \beta_{2,AMG} = \frac{1}{N}\sum_{i=1}^{N}\beta_{2i}, \beta_{3,AMG} = \frac{I}{N}\sum_{i=1}^{N}\beta_{3i}, \beta_{4,AMG} = \frac{I}{N}\sum_{i=1}^{N}\beta_{4i}, \beta_{5,AMG} = \frac{I}{N}\sum_{i=1}^{N}\beta_{5i}, \delta_{1,AMG} = \frac{I}{N}\sum_{i=1}^{N}\delta_{1i}, \quad (A11)$$

Nonlinear Model:

$$\beta_{1,AMG} = \frac{1}{N}\sum_{i=1}^{N}\beta_{1i}, \beta_{2,AMG} = \frac{1}{N}\sum_{i=1}^{N}\beta_{2i}, \beta_{3,AMG} = \frac{I}{N}\sum_{i=1}^{N}\beta_{3i}, \beta_{4,AMG} = \frac{I}{N}\sum_{i=1}^{N}\beta_{4i}, \beta_{5,AMG} = \frac{I}{N}\sum_{i=1}^{N}\beta_{5i}, \pi_{1,AMG} = \frac{I}{N}\sum_{i=1}^{N}\pi_{1i}, \quad (A12)$$

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