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Achieving net-zero emission target in Africa: Are sustainable energy innovations and financialization crucial for environmental sustainability of sub-Saharan African state?

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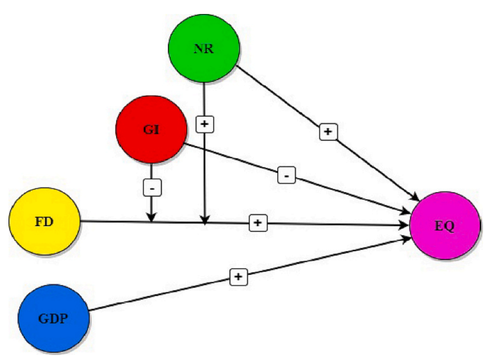
HIGHLIGHTS

- Moderating aspects of green innovations and financialization in environmental quality examined.
- Green innovations significantly abate pollution while financialization is detrimental.
- Interactive influence of innovations and financial development abates ecological depletion.
- Policy frameworks for net-zero emission are achievable from green innovation perspectives.

GRAPHICAL ABSTRACT



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ABSTRACT

Following the rising importance of energy transition in the environmental sustainability discussion, it is imperative to understand the roles of sustainable energy innovations and financialization to reach informed inferences for policy formulation. We examined the environmental quality performance in Sub-Sahara Africa using the case of the resource-rich Ghanaian state vis-à-vis the possible moderating influence of green innovations and financial development. The empirical analysis encompassed various estimation issues, including structural breaks, heteroscedasticity, and normality in data structure. We simulated with the dynamic autoregressive-distributed lag technique and confirmed that financialization, resource rents, and economic growth are significant positive determinants of pollutant emissions. However, green innovations decrease the rate of pollution in the nation. Moreover, the interaction between green innovations and financial development improves ecological quality, while that between natural resources and financial development spurs pollution in

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the ecosystem. Furthermore, causal connections in the series indicated unidirectional causalities from green innovations, financialization, natural resource rents, and economic growth to pollutant emissions. However, the interactive terms between green innovations and financial development and between natural resource rents and financial development are bi-directionally related to ecological pollution. Hence, the study essentially suggests that the net-zero emission agenda of the Paris Accord is achievable from higher investments in green innovations while harnessing the benefits of international financial flows to boost the sustainability capacity of the Sub-Saharan Ghanian economy.

Nomenclature

Abbreviations

SSA	Sub-Sahara Africa
DARDL	dynamic autoregressive-distributed lag
CO_2	Carbon dioxide emissions
CH_4	Methane
NR	Natural resources
LM	Lagrange Multiplier
N_2O	Nitrous oxide
GI	Green Innovation
PM2.5	Particulate matter 2.5
GII	Green Innovation index
SDGs	Sustainable development goals
EKC	Environmental Kuznets Curve
EQ	Environmental quality
FD	Financial development
GDP	Gross domestic product
SH	Slope homogeneity
ADF	Augmented Dickey-Fuller
ECT	Error Correction Term
DF-GLS	Dickey-Fuller Generalized Least Squares
ARDL	Auto Regression Distributed lag
ERT	Environment-related technologies
R&D	Research and development
FIN	Financial Development Index

1. Introduction

Establishing the connection between financial development (FD) and environmental quality (EQ) can be a complex task as many factors pose potential influences on the possible outcomes. In the Sub-Sahara African country of Ghana, this relationship is further complicated by a unique set of challenges as the country seeks to promote economic growth, safeguard its natural resources, and transition to a cleaner energy system [1]. While it is necessary to understand the FD and EQ nexus, it has become even more crucial to investigate how noticeable factors such as clean energy innovation and natural resource rent affect the relationship [2]. The argument is that if green innovations (GI) and natural resource rent (NRR) individually influence environmental quality, then their respective interactions with FD could portend substantial impacts on EQ. However, no empirical evidence validates this claim despite the implied relevance. Coupled with the lack of evidence is the fact that the extant studies on FD and EQ remain contentious. First, there are conflicting theoretical perspectives in the literature, with some suggesting that financial development leads to improved environmental quality while others argue otherwise. For instance, Zaidi et al. [3] advanced that a well-developed financial sector promotes ecological quality by providing funds for eco-friendly technologies and clean energy infrastructure. However, a contrary view by Musah et al. [4] indicates that the environment is undermined by growth through industrialization fueled by financial development. Second, there are contradictions in the empirical findings as several studies have found positive, negative, and insignificant relationships between FD and EQ (see [5,6,7]). The literature also lacks empirical evidence on how financial development indirectly impacts environmental quality through other perceptible factors [8].

Given the inconsistencies in the literature and the lack of empirical evidence on related indirect channels, this study seeks to investigate the relationship between FD as seen in the advancement in financial status and quality of the environment in Ghana, considering the likely moderating roles of green innovations and influences of other factors like natural resource rents. To attain this goal, providing answers to the following research questions is very essential; (1) what is the relationship between financial development and EQ? (2) what relationship exists between green innovations and EQ? (3) what is the association between natural resources and environmental quality? (4) do green innovations and natural resources significantly influence the FD-EQ links? (5) Does FD have a nonlinear association with EQ? Answers to these questions will provide valuable insights for policymakers and stakeholders looking to encourage not only economic progress but further address environmental concerns as well.

The contributions and merits of the study to the literature include the introduction of a new perspective on measuring the variables of interest, specifically EQ, GI and FD. For example, methane (CH_4) emissions, nitrous oxide (N_2O) emissions, PM2.5, and CO_2 emissions are used to construct an environmental quality index (EQI) for our analysis. This approach is in line with the study of Abid et al. [9], however, at variance with Kwakwa et al. [10] work on Ghana and Nibedita & Irfan [11]'s research on E7 economies who proxied EQ by only CO_2 emissions. Also, the market capitalization of listed domestic companies and the total value of stocks traded are included in the FD index (FIN) calculation. This approach builds on previous methodologies outlined in [12,13]. Additionally, R&D expenditures related to environmental protection were checked, including resident and nonresident patent applications, and the development of environmentally related technologies in constructing the GI index. This is a departure from previous literature, which only used the development of ecologically associated technologies as a proxy for GI (see [14,15,16,17,18]). Furthermore, upon thorough scrutiny of the literature, no study in Ghana has specifically examined the connection between FD & EQ while considering any indirect channels through which green innovations and natural resource rents impact the relationship. This study constitutes an initial effort and fills a gap in the literature. Methodologically, we employ a dynamic autoregressive-distributed lag (DARDL) technique that is modern and corrects the lapses of the conventional ARDL technique, and other traditional econometric methods. Based on our awareness, this technique is yet unexplored for the link between FD and ecological quality in Ghana, while accounting for the moderating roles of GI and NRR. Finally, because the affirmation of long-run connection amidst series does not necessarily imply causation, the gradual shift causality test of Nazlioglu et al. [19], which builds on the Toda and Yamamoto [20] approach was engaged to explore the causal paths analysis. As much as we are aware, prior research conducted on Ghana failed to adopt this approach.

The remainder of the present study is given in this pattern, Section 2 provides a framework that discusses the background and a review of relevant literature. Section 3 profiles the methodology and the dataset used in the study. Section 4 and 5 show the results and conclusion, respectively.

2. The literature exploration

In the aftermath of the groundbreaking research of [21], several studies explored the environment-growth linkage under the auspices of the Environmental Kuznets Curve (EKC). The conclusions of these studies have been mixed as some argue its invalidity [22], and others support its existence with empirical findings [23]. Other studies further argued about the treatment of EKC in isolation from other perceptible indicators of economic development. The general notion is that there could be some shortfalls in studying the environment-growth linkage without considering other factors influencing economic progress at large [8]. It is in this context that FD becomes prominent in the carbon emission model. According to Abbasi and Riaz [24], the question of how big the financial sector is is critical to the structural changes that accompany economic development. Therefore, omitting FD from the carbon emission model is unreasonable and may lead to unreliable outcomes. We thereby review studies investigating the FD-EQ link as well as including the variables that impact this link.

2.1. Connecting financial development (FD) to environmental quality (EQ)

Despite the theoretical relevance, the extant works on the FD-EQ link are characterized by two opposing views [8]. On one hand, a view shows that financial sector improvement enhances environmental quality. That is, economies with strong financial systems draw foreign direct investment and intensify their R&D efforts, ultimately raising EQ [25,26]. Tadesse [27] and Zagorchev et al. [28] also claimed that financial development enables technological advancements that stop environmental damage by promoting economic growth. Some authors advanced that well-developed financial structures aid EQ by providing the required capital for green techs and clean energy infrastructures (like [3,29]). In the study of Kamal et al. [30], financial development improved ecological quality by mitigating carbon emissions. Chiu and Zhang [31] researched 37 OECD nations over the period 1990–2015. From the results, financial development negatively moderated the connection between green energy and pollutant emissions.

Contrary to these views, other studies suggest that financial development may worsen environmental quality. Musah et al. [4] argue that industrialization, which may result in industrial pollution and a decline in environmental quality, could be fueled by FD. Ju et al. [32] report that FD damages ecological quality in 21 Arab nations. According to Duan et al. [33], the scale and structural effects of financial development promote environmental deterioration in 28 Chinese provinces. In Shahzadi et al. [34] investigation of G-7 economies, financial development harmed ecological quality by spurring more carbon emissions. As reported by Udeagha and Breitenbach [35], financial development permanently and temporarily harmed ecological sustainability in South Africa. Tinoco-Zermeño [36] researched 23 developing economies from 2001 to 2019. From the findings, financial development and ecological degradation were flanked by a bidirectional association.

Other studies reveal the various channels through which financial development undermines ecological quality within the same context. For the household effect channel, financial development allows consumers to easily access low-cost credit to patronize energy-demanding items (air conditioners, irons, dishwashers, etc.), which increases energy consumption [37]. The business effect channel explains how financial development lowers the cost of capital, allowing firms to hire more workers, buy more machines and equipment, and build or buy additional factories, which increases emissions from more energy usage [38,39,40]. The wealth effect channel underscores that a developed financial system can enhance risk diversification to ensure economic wealth creation [41]. It is worth noting that three different empirical findings back the contradictions in theoretical arguments. In West Africa, Prempeh [42] investigated the association between financial development and environmental quality and discovered that financial development harmed environmental quality in low and high-emitter countries, but had a neutral effect in medium-emitter economies. Besides, Chen et al. [43] affirmed financial development as detrimental to environmental quality in 34 African countries. Based on the conflicting findings, we hypothesize that:

H1. Financial development has a positive or negative effect on environmental quality.

2.2. Natural resources and environmental quality

Natural resource rent refers to the income generated by extracting and using natural resources, such as minerals, oil, and timber. It shows how the market value of the resources differs from the cost of getting or extracting them. Shahabadi and Feyziand [44] found that natural resource abundance attracts the inflows of FDI, which come along with energy-efficient technologies that help to improve the environment. Also, looking at Balsalobre-Lorente et al. [45]'s investigation of five EU economies, they affirmed natural resources as an encouraging factor of environmental quality, while other macroeconomic indicators are detrimental. On the contrary, Danish et al. [46] suggest that abundant natural resources minimize the reliance on imported contaminated energies that could harm the ecosystem. The authors agree with Miao et al. [47] that a country's availability of resources would discourage dependence on external energy imports thereby boosting its use of home sources that emit fewer greenhouse gases. However, according to Awosusi et al. [48], natural resource extraction weakens ecological quality due to economic improvement induced by a rise in industrial and other energy-polluting activities. Kwakwa et al. [49] and Dingru et al. [50] underscored similar conclusions but ascribed a worsening environment to the high volumes of energy used in the extraction and disposition of related waste. Nwani et al. [51] studied developing and transition economies from 1995 to 2017. From the results, economic reliance on natural resources harmed ecological quality in the nations. Over the period 1980 to 2018, Itoo and Ali [52] conducted a study on India and confirmed that natural resource depletion harmed the ecosystem of the nation. Sibanda et al. [53] adopted the GMM technique to study the determinants of ecological pollution in 42 resource-rich SSA countries. In a different study, Onifade [54] also observed that resource rent intensifies ecological degradation among oil-exporting African economies. Based on the estimates, natural resources harmed ecological safety. Wang et al. [55] looked at the Chinese case. From the estimates natural resource development positively impacted the prices of carbon emissions in the nation. Raihan [56] investigated the determinants of ecological quality in Uruguay and reported that natural resources harmed ecological quality in the nation. In Sub-Saharan Africa, Afolabi [57] research confirmed natural resources as harmful to environmental quality in resource-dependent economies. According to the study by Erdogan [58], natural resources damaged environmental sustainability in 13 Africa countries. Given the literature reviews, we hypothesize as follows.

H2. Natural resources have an ambiguous influence on environmental quality.

2.3. Green innovations and environmental quality

Focusing on green innovation, the impact on environmental quality is direct and even more amplified in its definition. Albort-Morant et al. [59] define green innovation as the distribution of capital in environmentally friendly projects and companies that positively impact the environment. These projects and companies can include renewable energy, clean technology, sustainable agriculture, corporate social responsibility (CSR) green supply chain activities and conservation efforts. According to Ganda [60], innovative technologies create a framework for green energy sources, thereby curtailing carbon emissions and other damaging pollutants. Similar conclusions were given by Abid et al. [61]. The former believes innovations related to the ecosystem are effective ways to address environmental issues, while the latter suggests that GI promotes EQ via green patents and technology. Alola & Onifade [62], Hordofa et al. [63], and Alola & Onifade [64] have also observed eco-innovations to be advancing ecological sustainability in different nations. Kirikkaleli et al. [65] investigated the determinants of ecological quality in Denmark and confirmed environmental innovations as gainful to ecological sustainability. In Africa, Udeagha and Breitenbach [66] reported that innovative technologies boosted ecological quality in South Africa. Also, Obobisa et al. [67] confirmed green technology as beneficial to environmental quality in 25 African countries. Aside from the observed direct effect of green innovations, some other studies have also observed the indirect desirable environmental impacts of innovations since they boost capacity for greener transition [68,69,70,71,72]. Hence, based on the above reviews, we formulate our third hypothesis as follows.

H3. Green innovations have a beneficial effect on the environment.

2.4. Interactive effects

Besides, green innovation may have an indirect effect on EQ through financial development, because the incorporation of green technologies in the financial system could curtail the damaging effects of the financial sector on economies. Also, revenues from natural resource activities could promote development in the financial sector. However, well-developed financial systems make it easy for businesses and households to access low-cost financial facilities to go in for polluting appliances and equipment thereby worsening environmental quality. In the study of Ali et al. [73], the moderation between green technology and financial development abated emissions in OECD economies. Also, innovative technologies mitigated the damaging effects of financial development on climate change in Jinqiao et al. [74] research on seven emerging economies. Besides, Ganda [75] reported that the interaction between natural resources and financial development reduced emissions in BRICS economies. Upon thorough review of the literature, there has been no study on how green innovations and natural resources influence the financial development and environmental quality relationship in the Ghanaian context. This study seeks to fill that gap. In doing so, the following research hypothesis is formulated for testing.

H4. Green innovations and natural resources significantly moderate the connection between financial development and environmental quality.

2.5. Review remarks on current gaps

In summary, the existing literature presents opposing views on the FD-EQ link. The contradictions signal the need for further analysis, particularly the indirect channels through which FD may influence environmental quality. While several variables have been used to explore these indirect channels, what is somewhat lacking is a study looking into how green innovation and natural resources moderate FD in impacting overall EQ levels. The present study fills such an existential literature gap.

3. The methodology section

3.1. The sources of data

The study period was chosen in view of the availability of data on the variables of concern which suggests the utilization of only the time series observation for Ghana to cover 1990–2018 periods. Data on natural resource rents (NRR) and income (GDP) came from the database of the World Bank (WDI), while the PCA technique was used to compute indices for environmental quality (EQ) in (Table 1, Table 2, and Table 3), financial development, and green innovations (GI). Carbon footprint has been widely used as a measure of ecological quality. However, according to Usman et al. [76] and Saqib and Benhmad [77], environmental deterioration is not a unitary phenomenon, as it encompasses many issues. This suggests that measuring environmental performance via a single indicator may result in misleading outcomes [78]. Therefore, in recent times, many scholars, in their attempt to measure ecological quality, have relied mostly on composite indices that consider a lot of environmental pollution [79]. Aside from CO_2 emissions which essentially cover over 70% of global greenhouse (GHG) emissions [80], methane (CH_4) emissions, nitrous oxide (N_2O) emissions, and PM2.5 also contribute materially to climate change issues in the globe. Therefore, following Abid et al. [9], the above series was used to construct an environmental quality index (EQI) for our analysis.

Studies by Samargandi and Sohag [81], Nurgazina et al. [82], and Zhang et al. [83] measured FD by domestic credit to the private sector, while Geyikci et al. [84] used market capitalization of listed domestic companies to indicate FD. Hung [12] and Musah et al. [13] constructed an index to measure FD using broad money, broad money growth, domestic credit to the private sector, and the ones by banks as indicators, while, Wang et al. [85], Usman et al. [86], and Awosusi et al. [87] used the index developed by the International Monetary Fund (IMF) that takes into consideration the effectiveness, depth, and access of financial markets and institutions as a surrogate of FD. We extend the approaches of Hung [12] and Musah et al. [13] by including the market capitalization of listed domestic companies and the total value of stocks traded as additional variables to compute a FD index (FIN) for our analysis.

Unlike Habiba et al. [15], Tariq et al. [18], Gao et al. [14], Jin et al. [17], and Hafeez et al. [16] who proxied GI by only development of environmentally related technologies, we exhibited novelty by using R&D spendings related to the protection of the environment, resident and nonresident patent applications, and development of environmentally related technologies to construct a GI index (GII) for our analysis. As far as we are aware, there has been no study on Ghana that adopted this unique approach. Following Hung [12] and Musah et al. [13], EQI, FIN, and GII were computed in line with the linear combination of the variables of concern.

The PCA outcomes are displayed in Table 1 to Table 3. In Table 1 and Table 3, the first three components were responsible for 95% and 96% of the variations in the estimated EQI and GII respectively, while the first four components in Table 2 catered for 98% of the variances in the estimated FIN. Moreover, the components' corresponding eigenvalues

Table 1
The analysis (PCA) for environmental quality (EQ) Index (i.e, EQI).

The Components	The Eigenvalue	Estimated Difference	Given Proportion	The Cumulative
1st Comp	2.641	1.496	0.660	0.660
2nd Comp	1.145	1.017	0.286	0.946
3rd Comp	0.128	0.732	0.032	0.978
4th Comp	0.086	–	0.022	1.000

Subsequent Eigenvectors (Loadings)				
Variable	1st Comp	2nd Comp	3rd Comp	4th Comp
Carbon dioxide emissions (CO_2)	0.498	−0.543	0.651	0.184
Methane emissions (CH_4)	0.509	−0.135	−0.655	0.542
Nitrous oxide emissions (N_2O)	0.484	0.821	0.287	0.098
Particulate matter 2.5 (PM2.5)	0.509	−0.114	−0.255	−0.814

Table 2
The analysis (PCA) for Green innovation (GI) index (i.e, GII).

The Components	The Eigenvalue	Estimated Difference	Given Proportion	The Cumulative
1st Comp	1.806	0.262	0.452	0.452
2nd Comp	1.544	0.962	0.386	0.838
3rd Comp	0.582	0.514	0.146	0.984
4th Comp	0.068	–	0.017	1.000

Corresponding Eigenvectors (Loadings)				
Variable	1st Comp	2nd Comp	3rd Comp	4th Comp
Development of environment-related technologies	0.063	0.994	0.084	0.008
Research and development expenditure related to environmental protection	0.547	−0.105	0.835	0.011
Patent applications (residents)	0.594	−0.001	−0.375	−0.712
Patent applications (nonresidents)	0.587	−0.100	−0.393	0.703

were >1 indicating that they were very substantial. Because the explanatory powers of the fourth components in Table 1 and Table 2, and the fifth and sixth components in Table 3 were very low, they were not considered in the index computation process. Besides, all the series had significant loadings based on estimates depicted in the tables. This suggests that the series met all the necessary conditions to be considered in computing the indices.

The variables were selected after taking into consideration the SDG targets. Particularly, SDG 13 (climate action); SDG 16 (peaceful and inclusive societies for sustainable development); SDG 12 (responsible consumption and production); SDG 14 (healthy oceans and seas); SDG 11 (sustainable cities and societies); SDG 3 (health and well-being among the citizenry); SDG 7 (accessibility to modern and sustainable energy); SDG 8 (sustainable economic progress); and SDG 15 (healthy land, forests and biodiversity). To attain these goals, it is pertinent to reduce ecological pollution while increasing biocapacity at the same time. This formed the focal point of this exploration. Further information on the series is detailed in Table 4.

3.1.1. Theoretical background and model specification

The scale, composition, and technique effects have been expansively used to examine the environmental impacts of financial development. Advocates of the scale effect contend that financial development increases output, which results in the use of more energy thereby polluting the environment. According to the composition effect, development in the financial sector has the potential to influence countries to switch from the importation and exportation of commodities to the manufacturing of goods, which comes with a lot of environmental implications. The technique effect postulates that advancement in the financial sector promotes the adoption of eco-technologies thereby boosting environmental quality.

Moreover, the ecological modernization and endogenous growth theories support the association between green technology and environmental performance. The ecological modernization hypothesis states that societies can attain environmental quality by embracing cutting-edge technologies and eco-friendly practices [88]. According to this theory, the development and application of green technologies can help a society lessen its environmental externalities. Likewise, the endogenous hypothesis suggests that internal factors are more essential for economic development than external factors [74]. According to this hypothesis, development in technology can promote continuous economic development while also safeguarding the environment [89]. This is because improving innovative technologies reduces input requirements and maximizes economic output while taking into consideration environmental concerns through efficient energy utilization.

Finally, the resource curse hypothesis explains a scenario in which nations endowed with abundant resources suffer from slow economic development. This is because the nations concentrate all their productive resources on a few industries, like mining and oil production, at the expense of other industries that could promote economic growth. For certain economies, natural resources are beneficial since they serve as a primary engine for economic growth. But when the resources are overexploited resulting in environment degradation, they become a curse by preventing the nations from achieving sustainable development. Besides, the level of climate change within an economy is predicted by the amount of natural resources used for economic growth [90]. Consequently, the kind of resources used for economic output is a crucial factor in determining climate change [91,92].

The above background serves as the foundation for examining the nexus between financial development and environmental quality, accounting for the moderating roles of green innovations and natural resources. To accomplish this goal, the following function is specified as

$$EQI = f(FD, GI, NR, GI{*}FD, NR{*}FD, GDP) \quad (1)$$

where environmental quality index (*EQI*) is the response variable; financial development (*FD*), green innovations (*GI*), and natural resource rents (*NR*) are the main predictors of concern; *GI*FD* is the interactive term between *GI* and *FD*; *NR*FD* is the interactive term between *NR* and *FD*; and income (*GDP*) is the control variable to help minimize model specification bias. The aforestated model is expressed in a linear econometric specification in Eq. (2).

Table 3
The analysis (PCA) for financial development (FD) index (i.e, FIN).

The Components	The Eigenvalue	Estimated Difference	Given Proportion	The Cumulative
1st Comp	1.890	0.279	0.315	0.315
2nd Comp	1.611	0.358	0.269	0.584
3rd Comp	1.253	0.618	0.209	0.793
4th Comp	0.635	0.291	0.106	0.899
5th Comp	0.344	0.077	0.057	0.956
6th Comp	0.267	–	0.044	1.000

The Eigenvectors (Loadings)						
Variable	1st Comp	2nd Comp	3rd Comp	4th Comp	5th Comp	6th Comp
Broad money	0.555	−0.256	0.382	0.034	−0.037	−0.691
Domestic credit to the private sector by banks	0.080	0.668	0.171	−0.439	0.553	−0.140
Broad money growth	0.579	−0.329	0.155	−0.202	0.269	0.648
Domestic credit to the private sector	0.382	0.211	−0.532	0.636	0.346	−0.053
The market capitalization of listed domestic companies	−0.199	0.147	0.716	0.601	−0.689	0.203
Stocks traded, total value	0.407	0.561	0.074	0.023	0.157	0.198

Table 4
Data description and measurement units.

All Variables	Ensuring Symbol	The Measurements	Obtained from
Gross domestic product	GDP	Per capita (Constant 2015 US$)	WDI
Total natural resource rents	NR	Percentage (%) of GDP	WDI
Variables for Environmental Quality Index (EQI)			
Using Carbon dioxide emissions	CO_2	Metric tons per capita	WDI
Using Methane emissions	CH_4	Kt of CO_2 equivalent	WDI
Using Nitrous oxide emissions	N_2O	Thousand metric tons of CO_2 equivalent	WDI
With PM2.5 air pollution, mean annual exposure	PM	Micrograms per cubic meter	WDI
Variables for Financial Development Index (FIN)			
With Broad money	BM	Percentage (%) of GDP	WDI
With Domestic credit to the private sector by banks	DCB	Percentage (%) of GDP	WDI
Using Broad money growth	BMG	Annual percentage	WDI
With Domestic credit to the private sector	DCP	Percentage (%) of GDP	WDI
Using Stocks traded, total value	ST	Current US$	WDI
With the Market capitalization of listed domestic companies	MC	Percentage (%) of GDP	WDI
Variables for Green Innovation Index (GII)			
Development of environment-related technologies	ERT	Percentage (%) of all technologies	OECD
With Research and development expenditure related to environmental protection	R&D	Percentage (%) of GDP	OECD
Patent applications (residents)	PAR	Annually	WDI
Patent applications (nonresidents)	PAN	Annually	WDI

$$EQI_t = a_o + \beta_1 FD_t + \beta_2 GI_t + \beta_3 NR_t + \beta_4 (GI^*FD)_t + \beta_5 (NR^*FD)_t + \beta_6 GDP_t + \mu_t \quad (2)$$

where $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$,and β_6 are the elasticities of *FD*, *GI*, *NR*, (*GI*FD*), (*NR*FD*), and *GDP* respectively; a and μ are the respective autonomous term and error component while the t is for the studied time frame. The given series in Eq. (1) are log-transformed to help control for skewness and heteroscedasticity [93]. The log-linear specification of the above model is in the subsequent Eq. (3)

$$lnEQI_t = a_o + \beta_1 lnFD_t + \beta_2 lnGI_t + \beta_3 lnNR_t + \beta_4 ln(GI^*FD)_t + \beta_5 ln(NR^*FD)_t + \beta_6 lnGDP_t + \mu_t \quad (3)$$

where *lnEQI*, *lnFD*, *lnGI*, *lnNR*, *ln*(*GI*FD*), *ln*(*NR*FD*), and *lnGDP* are the log transformations of the items in Eq. (2), and $\beta_1, \ldots \beta_6$ are the parameters to be estimated. Variables in Eq. (3) follow the definition of the former Eq. (1).

Several researchers hold conflicting opinions on the association between FD and EQ. As formerly argued, a well-developed financial sector helps to provide funds or incentives for eco-friendly technologies, and clean energy infrastructure that help to advance EQ [3]. Also, a sound financial system promotes investments in energy efficiency, and R&D activities that help the EQ levels. In contrast, growth in the financial sector helps to improve the living conditions of households, as such, they can afford more pollutant products, that end up degrading the environment [4]. Also, FD helps businesses to have access to more machinery and production appliances that are much more energy-intensive, thereby creating higher ecological pollution [94]. Based on the above, the coefficient of FD may turn up as positive $\left(\beta_1 = \frac{\partial lnEQI_{it}}{\partial lnFD_{it}} > 0\right)$ or even negative $\left(\beta_1 = \frac{\partial lnEQI_{it}}{\partial lnFD_{it}} < 0\right)$. Besides, GI promotes EQ via green patents and green technology [9]. Innovations related to the ecosystem can be effective ways to address environmental issues. As indicated by Ganda [60], innovative technologies create a framework for green energy sources, greatly curtailing carbon emissions and other damaging pollutants. We therefore predict the parameter of GI to be negative $\left(\beta_2 = \frac{\partial lnEQI_{it}}{\partial lnGI_{it}} < 0\right)$.

Moreover, natural resource extraction improves economic expansion [87], and as the economy expands, manufacturing, industrial, and other economic activities that are reliant on polluting energies also increase, thereby weakening ecological quality. Kwakwa et al. [49] reported that resource extraction threatens EQ via the high volumes of energy used in the extraction and disposition of wastes. However, according to Danish et al. [46], the abundance of natural resources minimizes the reliance on imported contaminated energies that could harm the ecosystem. Shahabadi and Feyziand [44] postulate that natural resource abundance attracts the inflows of FDI, which come along with energy-efficient technologies that help to improve the environment. Balsalobre-Lorente et al. [45] work show resources as friendly to EQ, while other macroeconomic indicators were damaging to it. According to the authors, the negative association between natural resources and ecological pollution implies, that the abundance of natural resources helps to promote environmental sustainability, as such the importation of polluting energies is of no necessity. With reference to the above, we project the coefficient of natural resources to be either positive $\left(\beta_3 = \frac{\partial lnEQI_{it}}{\partial lnNR_{it}} > 0\right)$ or negative $\left(\beta_3 = \frac{\partial lnEQI_{it}}{\partial lnNR_{it}} < 0\right)$, supporting the studies of Usman & Balsalobre-Lorente [95].

Green innovations have proven to be beneficial to ecological safety [96]. If the variable is friendly to EQ, then its interaction with FD could help to promote a sustainable environment. We, therefore, expect the interactive term between GI and FD (*GI*FD*) to be negatively related to ecological pollution ($\beta_4 < 0$). Also, natural resources can have an indirect impact on the environment through the route of FD. This implies the abundance of resources could be vital in spurring or mitigating the environmental effects of FD in economies. We therefore predict the sign of the interactive term between NR and FD (*NR*FD*) to be either positive ($\beta_5 > 0$) or negative ($\beta_5 < 0$).

Besides, economic growth could have a detrimental effect on ecological quality if not managed properly. Grossman and Krueger [21] indicated scale, composition, and technique effects as the three channels through which growth impedes a better environment. Following the scale effect, more resources and inputs are used to produce more commodities at the start of the economic growth path. Therefore, as energy production swells up so do pollutant emissions and greenhouse gases [97]. The majority of nations found in this stage are developing economies, as such economies support economic advancement at the expense of their environments. The composition effect stipulates that economic progress produces structural change. Thus, as national production increases, the economy's structure shifts towards less polluting economic activities. Transitions from intensive industrial sectors to the service sector are characterized by this economy [97]. The technique effect is the final growth-related channel that has an impact on the environment. When high-income economies spend more on research and development, new technical processes emerge, and old, polluting technologies are replaced with modern ones. As a result, the quality of the environment improves [98]. Therefore, with reference to the above, we assume either a positive link for the income factor $\left(\beta_6 = \frac{\partial lnEQI_{it}}{\partial lnGDP_{it}} > 0\right)$ or a negative link $\left(\beta_6 = \frac{\partial lnEQI_{it}}{\partial lnGDP_{it}} < 0\right)$.

3.1.2. Estimation strategies

Because non-stationary data increases the likelihood of getting unreliable results [99,100], it was worthwhile to examine whether the series were stationary or not. We then harnessed the KPSS, ADF, PP & the DF-GLS unit root processes that are very fitting for time series analysis of series' integration orders. Conversely, since, they are limited because they don't cover structural breaks [101,102,103], we further include the Zivot and Andrews [104] technique when assessing the series' integration orders. This test is built on the unit root testing procedure of Perron [105] (hereafter Perron). A major criticism of Perron's approach is that his choice of breakpoints was reliant on prior observation of data. This implies any limitations affiliated with pre-testing are also applicable to his approach. Perron's test tests the null hypothesis of unit root with drifts that do not account for structural change, while the alternative hypothesis is a trend-stationary unit root that allows for a one-time structural break in the trend. Zivot and Andrews [104] transformed Perron's procedure, which is conditional on a known breakpoint, into a unit root test which is unconditional. Specifically, their approach permits a break in the trend composition within the hypothesized (H_1) following operations in Eqs. (4–6).

$$\Delta z_t = \vartheta_1 + \vartheta_2 t + \xi z_{t-1} + \psi DU_t + \sum_{i=0}^{r} \omega_i \Delta z_{t-i} + \varepsilon_t \tag{4}$$

$$\Delta z_t = \vartheta_1 + \vartheta_2 t + \xi z_{t-1} + \delta DT_t + \sum_{i=0}^{r} \omega_i \Delta z_{t-i} + \varepsilon_t \tag{5}$$

$$\Delta z_t = \vartheta_1 + \vartheta_2 t + \xi z_{t-1} + \psi DU_t + \varphi DT_t + \sum_{i=0}^{r} \omega_i \Delta z_{t-i} + \varepsilon_t \tag{6}$$

where r is the predictors' upper limit lag length, T_b is the breakpoint and $DU_t = 1$. Also, if t > T_b then DT_t will be equivalent to t-T_b. Otherwise, it will be zero. After these processes, the ARDL bound test of Pesaran et al. [106] with the Kripfganz and Schneider [107] critical values and approximate *p*-values were first conducted to examine whether the series were materially cointegrated in long-run terms. This test is advantageous because it is applicable for series that are purely I(0), purely I(1) or mutually cointegrated [106]. The model developed for the bound test of this exploration was specified in Eq. (7).

$$\begin{aligned} \Delta lnEQI_t = {} & \varphi_0 + \varphi_1 lnEQI_{t-1} + \varphi_2 lnFD_{t-1} + \varphi_3 lnGI_{t-1} + \varphi_4 lnNR_{t-1} \\ & + \varphi_5 ln(GI^*FD)_{t-1} + \varphi_6 ln(NR^*FD)_{t-1} + \varphi_7 lnGDP_{t-1} \\ & + \sum_{i=1}^{p} \beta_{1i} \Delta lnEQI_{t-1} + \sum_{i=1}^{q} \beta_{2i} \Delta lnFD_{t-1} + \sum_{i=1}^{q} \beta_{3i} \Delta lnGI_{t-1} \\ & + \sum_{i=1}^{q} \beta_{4i} \Delta lnNR_{t-1} + \sum_{i=1}^{q} \beta_{5i} \Delta ln(GI^*FD)_{t-1} + \sum_{i=1}^{q} \beta_{6i} \Delta ln(NR^*FD)_{t-1} \\ & + + \sum_{i=1}^{q} \beta_{7i} \Delta lnGDP_{t-1} + u_t \end{aligned} \tag{7}$$

where $\Delta$is the change operator, φ and β are the coefficients to be estimated, φ_0 is the constant term, and $t-1$ denotes the lags selected via the AIC. Eq. (7a) and Eq. (7b) provide the tested hypotheses.

$$H_0 : \varphi_{1,i} = \varphi_{2,i} = \varphi_{3,i} = \varphi_{4,i} = \varphi_{5,i} = 0 \tag{7a}$$

$$H_1 : \varphi_{1,i} \neq \varphi_{2,i} \neq \varphi_{3,i} \neq \varphi_{4,i} \neq \varphi_{5,i} \neq 0, \text{for } i = 1, \dots, 5 \tag{7b}$$

Under this test, cointegration is validated if the computed F-value is greater than the upper bound value. On the other hand, if the computed F-value is smaller than the lower bound value, the assumption of no cointegration cannot be rejected. Finally, there is no cointegration if the computed F-value lies between the upper bound value and the lower bound value. The bound test of Pesaran et al. [106] is very essential, however, with no considerations for structural breaks. Therefore, the Maki [108] cointegration test that is robust to the above issue was also performed. This test improves upon other tests for cointegration. The Hatemi-J [109] test allows for one structural break, while the Gregory and Hansen [110,111] test allows for two structural breaks. These tests would therefore yield biased estimates and inferences if the true number of breaks is more than two. To help resolve this challenge, Maki [108] proposed a cointegration test that allows for an unknown number of breaks. This test assumes that the maximum number of breaks is greater than or equal to the unspecified number of breaks of the cointegrating vector [108]. Apart from taking into account the unspecified number of breaks, this test is also computationally less intensive as compared to some other tests for cointegration. The test is based on the Bai and Perron [112] test for structural breaks and the Kapetanios [113] test for unit root. In a Monte Carlo simulation, the Maki [108] test performed better than the Gregory and Hansen [110] test and the Hatemi-J [109] test, when the cointegration association had persistent Markov Switching (MS) or multiple breaks. In testing for cointegration that allows for multiple structural breaks, the following regression models Eqs. (8–11) as proposed by Maki [108].

Model A: Level shift

$$Y_t = \rho + \sum_{i=1}^{k} \rho_i D_{i,t} + \theta' Z_t + u_t \tag{8}$$

Model B: Level shift with a trend

$$Y_t = \rho + \sum_{i=1}^{k} \rho_i D_{i,t} + \theta' Z_t + \sum_{i=1}^{k} \theta' Z_t D_{i,t} + u_t \tag{9}$$

Model C: Regime shifts

$$Y_t = \rho + \sum_{i=1}^{k} \rho_i D_{i,t} + \theta' Z_t + \sigma t + \sum_{i=1}^{k} \theta' Z_t D_{i,t} + u_t \tag{10}$$

Model D: Trend and regime shifts

$$Y_t = \rho + \sum_{i=1}^{k} \rho_i D_{i,t} + \theta' Z_t + \sigma t + \sum_{i=1}^{k} \sigma' D_{i,t} + \sum_{i=1}^{k} \theta' Z_t D_{i,t} + u_t \tag{11}$$

The Z_t & Y_t are the observables, D_i is the dummy variable, T_b is the period of breaks with the error component shown by u_t. After the cointegration tests, the elastic effects of the regressors on the regressand were explored. In this aspect, the DARDL method [114] was very efficient since it ameliorated the shortcomings of the older ARDL style of estimation. One other crucial importance is that this technique can plot the graphs of the counterfactual shocks (positive and negative) of a predictor on the response variable when the other predictors are held constant [82]. The DARDL technique can also estimate both the long and the short-run parameters of predictors as other methods do [115]. Simulations are done >5000 times under this technique using the series vector within a multivariate normal distribution in line with Eq. (12).

$$\begin{aligned} \Delta(y)_t = {} & \alpha_0 + \theta_0 (y)_{t-1} + \theta_1 (x_1)_{t-1} + \ldots + \theta_k (x_k)_{t-1} \\ & + \sum\nolimits_{i=1}^{p} (\alpha_i) \Delta(y)_{t-i} + \sum\nolimits_{j=0}^{q1} \beta_{1,j} \Delta(x_i)_{t-j} + \ldots + \sum\nolimits_{j=0}^{qk} \beta_{k,j} \Delta(x_k)_{t-j} + u_t \end{aligned} \tag{12}$$

where α_0 is the constant term, $t-1$ is the lags of the regressors, Δ is the change operator, and the first-difference lags of the explained & explanatory variables are shown as p and q respectively where the error component is the u. Based on Eq. (13), the following DARDL error correction models were developed for estimation;

$$\begin{aligned} \Delta lnEQI_t = {} & \alpha_0 + \theta_0 lnEQI_{t-1} + \theta_1 lnFD_{t-1} + \theta_2 lnGI_{t-1} + \theta_3 lnNR_{t-1} \\ & + \theta_4 ln(GI^*FD)_{t-1} + \theta_5 ln(NR^*FD)_{t-1} + \theta_6 lnGDP_{t-1} + \alpha_i \Delta lnEQI_{t-1} \\ & + \beta_1 \Delta lnFD_t + \beta_2 \Delta lnGI_t + \beta_3 \Delta lnNR_t + \beta_4 ln(GI^*FD)_t + \beta_5 ln(NR^*FD)_t \\ & + \beta_6 \Delta lnGDP_t + u_t \end{aligned} \tag{13}$$

where Δ is the change operator, α_0, t and u are standing for constant, period, and error composition in this order while short-term and long-term influences will be shown by $\beta' s$ and $\theta' s$ respectively. For robustness purposes, the ARDL technique of Pesaran and Shin [116] was also considered in the estimation procedures. This approach is advantageous because it is more robust and performs better for small sample-sized data

[117]. It is also flexible to use [118] and could be applied irrespective of whether the series are integrated of order I(0), I(1) or both [106]. Unfortunately, sampling uncertainty could be high as noted by Chudik et al. [119] if the rate of convergence to long-run is not fast enough and the time dimension is not sufficiently big. Besides, assuming series have trends, the dynamics in the approach are only approximated instead of proper dynamic modeling [106]. It is based on these limitations that the DARDL technique was advanced to improve the situation [13]. In line with Pesaran and Shin [116], the long-run coefficients were explored via the following ARDL specification in Eq. (14).

$$lnEQI_t = \alpha_0 + \sum_{i=1.0}^{p} \Phi_{1i} lnEQI_{t-1} + \sum_{i=1.0}^{q} \Phi_{2i} lnFD_{t-1} + \sum_{i=1.0}^{q} \Phi_{3i} lnGI_{t-1} + \sum_{i=1}^{q} \Phi_{4i} lnNR_{t-1} + \sum_{i=1.0}^{q} \Phi_{5i} ln(GI^*FD)_{t-1} + \sum_{i=1.0}^{q} \Phi_{6i} ln(NR^*FD)_{t-1} + \sum_{i=1}^{q} \Phi_{7i} lnGDP_{t-1} + u_t \quad (14)$$

where p and q are the lags selected through the AIC and Φ denotes the long-run variance. The short-run parameters were also computed through the ensuing relation Eq. (15).

$$\Delta lnEQI_t = \alpha_0 + \sum_{i=1.0}^{p} \kappa_{1i} \Delta lnEQI_{t-1} + \sum_{i=1}^{q} \kappa_{2i} \Delta lnFD_{t-1} + \sum_{i=1.0}^{q} \kappa_{3i} \Delta lnGI_{t-1} + \sum_{i=1}^{q} \kappa_{4i} \Delta lnNR_{t-1} + \sum_{i=1.0}^{q} \kappa_{5i} \Delta ln(GI^*FD)_{t-1} + \sum_{i=1}^{q} \kappa_{6i} \Delta ln(NR^*FD)_{t-1} + \sum_{i=1.0}^{q} \kappa_{7i} \Delta lnGDP_{t-1} + \phi ECT_{t-1} + u_t \quad (15)$$

where ECT is the error correction term and ϕ is its coefficient, which measures the adjustment speed to the equilibrium association. According to Khan et al. [120], the parameters of the ECT are often between -1 to 0. To authenticate the validity of the model, various diagnostic tests were conducted.

Following Khan et al. [121], the Ramsey RESET test was conducted to assess the accuracy of the model, while the Breusch-Godfrey (LM) method was performed to check for correlations (serial) in obtained errors. Moreover, the White's test was performed to check heteroscedasticity in residuals, while the Jarque-Bera test was conducted to assess normality in the residual terms. Finally, the Supremum Wald (SWALD) test was performed to check structural breaks in the model.

Because the regression techniques adopted for this exploration could not explore the causations amidst the series, the gradual shift causality test of Nazlioglu et al. [19], which builds on the Toda and Yamamoto [20] approach was engaged to explore the causal connections amidst the series. This technique employs the Fourier approximation and Toda-Yamamoto causality test to capture the causalities between output and input variables by considering smooth and gradual shifts (structural change). In line with Yuping et al. [122], the gradual shift causality method used in this exploration follows Eq. (16).

$$y_t = \sigma(t) + \beta_1 y_{t-1} + \ldots + \beta_{p+dmax} y_{t-(p+dmax)} + \varepsilon_t \quad (16)$$

where y_t denotes $lnEQI$, $lnFD$, $lnGI$, $lnNR$, $ln(GI^*FD)$, $ln(NR^*FD)$, and $lnGDP$; σ is the intercept; ε is the residual term, and β is the coefficient matrix. The above specification is a VAR $(p+d)$ model. The Fourier approximation process which captures the structural shifts is specified in Eq. (17).

$$\sigma(t) = \sigma_0 + \gamma_1 sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 cos\left(\frac{2\pi kt}{T}\right) \quad (17)$$

where k is the approximation frequency. By substituting Eq. (17) into Eq. (16), the causality of Toda-Yamamoto is thus expressed in Eq. (18).

$$y_t = \sigma_0 + \gamma_1 sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \ldots + \beta_{p+d} y_{t-(p+d)} + \varepsilon_t \quad (18)$$

The overall analytical procedure is illustrated in Fig. 1.

Table 5
Descriptive statistics and correlational analysis.

Descriptive statistics					
Statistic	LnEQI	LnFD	LnGI	LnNR	LnGDP
Mean	9.35	4.39	0.64	2.39	23.99
Median	9.36	4.43	3.18	2.40	23.91
Maximum	9.69	4.72	3.95	2.79	24.79
Minimum	9.05	3.62	2.40	1.85	23.30
Std. Dev.	0.19	0.22	1.30	0.25	0.47
Skewness	0.11	−1.53	1.58	−0.42	0.26
Kurtosis	2.02	6.70	3.72	2.41	1.75
Jarque-Bera	1.23	27.91	12.74	1.27	2.22
Probability	0.54	0.00***	0.00***	0.53	0.33
VIF		1.72	1.80	1.56	1.37
Tolerance (1/VIF)		0.58	0.55	0.64	0.73
Correlational analysis					
Variables	LnEQI	LnFD	LnGI	LnNR	LnGDP
LnEQI	1.00				
LnFD	0.79	1.00			
	(0.00)***				
LnGI	−0.56	−0.48	1.00		
	(0.02)**	(0.05)*			
LnNR	0.74	0.49	−0.50	1.00	
	(0.00)***	(0.04)**	(0.03)**		
LnGDP	0.96	0.32	0.17	0.20	1.00
	(0.00)***	(0.57)	(0.68)	(0.61)	

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

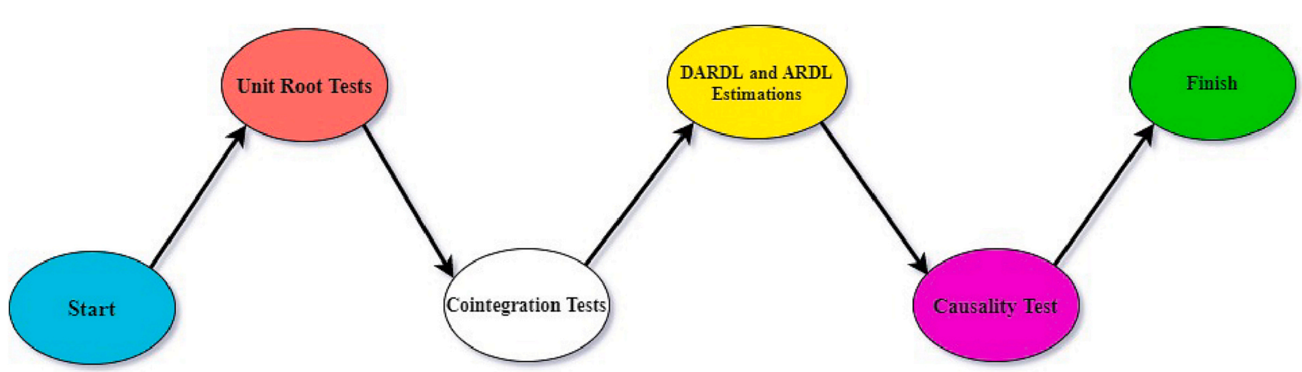

Fig. 1. Analytical procedure.

3.2. Discussions

3.2.1. Descriptive and correlational analysis

Summary statistics on the variables are displayed in Table 5. From the table, the twine of FD and GI are leptokurtic-shaped structures, while those of EQI, NR, and GDP are of platykurtic shape. Moreover, all the series are normally distributed except GI and FD. On the correlations amidst the variables, FD, NR and GDP have a strongly positive association with EQI. This signifies that the rise in FD, NR and GDP causes EQI to rise and vice versa. However, GI has a moderately negative relationship with EQI suggesting that the rise in the former causes the latter to fall and vice versa. Finally, the correlation coefficients between the predictors are all <0.7. This means multi-collinearity is not a problem in the series and the VIF also validates the test outcomes.

3.2.2. Unit root and cointegration analysis

Identifying the integration properties of series is necessary and we did use the DF-GLS, the ADF, and the PP methods as well. Table 6 contains the results indicating unit roots at level but at levels when applying these three listed approaches which overlooked structural breaks. Following Zivot & Andrews test, the structural breaks of the respective variables were located at EQI (2008), FD (2006), GI (2004), NR (1999), FD*GI (2001), FD*NR (1996), and GDP (1995). Later, the cointegration status was checked. This was achieved by the ARDL bound test shown in Table 7. There is confirmation of a sufficiently high F-statistic relative to the bound's values (for upper & lower levels). This implies there was cointegration in the assessed system. The Maki cointegration test was also performed for structural break reasons. Based on the estimates, the notion of a long-run cointegration link was reassured.

3.2.3. Regression analysis

3.2.3.1. General outcomes of the dynamic ARDL estimations. After affirming the series to be cointegrated in the long-run, the elasticities of the covariates were first explored via the DARDL technique. From the estimates depicted in Table 8, FD was a significantly positive determinant of EQI. All factors held constant, a percentage increase in FD promoted EQI by 0.946% and 0.447% in the long and the short run respectively. This suggests that FD was not friendly to ecological sustainability in Ghana. This is justifiable because development in the financial sector stimulates investments in infrastructure that lead to the use of more unclean forms of energy, thereby polluting the environment. Also, the financial sector raises the purchasing power of households, propelling them to go in for home appliances, automobiles and other products that are damaging to the ecology, due to their heavy reliance on polluting energies. Well-developed financial sectors offer funding support to businesses at low-cost. This helps them to buy more machines and equipment for production thus creating the excessive utilization of environmentally destructive conventional energy. Besides, the low-cost facilities improve the capital base of entities, as such, they can expand their scope. This might raise the level of energy demand and therefore, more pollutant emissions. According to Park et al. [126], FD is consequential to ecological quality in some EU economies because domestic credit to the private sector is mostly invested in projects that are harmful to the environment. In Shoaib et al. [127] comparative study, FD was a key promoter of pollutant emissions in developing nations than developed ones. However, Abid et al. [61] analysis affirms that FD is beneficial to environmental sustainability. Similarly, Paramati et al. [128] viewed FD as friendly to the ecology of developed economies because it provides investors with additional funding that could be invested in clean energy projects. Anees et al. [129] also documented FD as gainful to the ecology because it contributes to the development of energy-efficient technologies.

On the other hand, the coefficient of GI was negative and statistically significant. Specifically, a 1% rise in GI mitigated EQI by 0.775% and 0.291% respectively in the long and the short-run. This finding is justifiable because innovative technologies help to build modern and efficient technologies that help to promote ecological sustainability. As reported by Qamruzzaman et al. [130], environmental innovations minimize energy costs thereby speeding up the transition to low-carbon economies. Therefore, increasing investments in eco-technologies could help to minimize pollution in the ecosystem. Appiah et al. [131] and Onifade et al. [132], have observed that inadequate financialization is not just a major economic challenge alone, but also one of the major impediments to global energy transition desire. Implying that the desired energy transition cannot be achieved without proper investments in eco-technologies. Eco-technologies will help to boost renewable energy production and consumption. In addition, there is a need to establish relevant ecological policies and regulations to help propel all stakeholders towards embracing green technologies in their

Table 6
Unit root test results.

All Variables	PP		ADF		DF-GLS	
	The Level	The 1st Diff.	The Level	The 1st Diff.	The Level	The 1st Diff.
LnEQI	−1.987	−3.924***	−2.302	−4.645***	−1.713	3.784***
LnFD	−2.443	−4.767***	−1.851	−3.877***	−2.868	−5.944***
LnGI	−1.453	−3.124**	−2.502	−5.106***	−1.952	−3.951***
LnNR	−2.517	−5.328***	−1.317	−3.285**	−0.876	−2.607*
Ln(GI*FD)	−1.015	−2.694*	−2.886	−5.954***	−2.437	−4.994***
Ln(NR*FD)	−2.202	−4.511***	−2.743	−5.812***	−1.845	−3.898***
LnGDP	−1.835	−3.797***	−1.764	−3.821***	−2.761	−5.872***

Zivot and Andrew's test					
Variables	Levels		First Difference		Submissions
	Intercept & Trend	Break Year	Intercept & Trend	Break Year	
LnEQI	−3.552	2008	−6.715***	2005	I(1)
LnFD	−4.542	2006	−7.361***	2003	I(1)
LnGI	−3.317	2004	−6.426***	2002	I(1)
LnNR	−4.885	1999	−7.428***	1998	I(1)
Ln(GI*FD)	−3.572	2001	−6.884***	2000	I(1)
Ln(NR*FD)	−3.415	1996	−6.512***	1997	I(1)
LnGDP	−4.893	2007	−7.445***	1995	I(1)

Notes: PP represents Phillip and Perron's [123] test, ADF signifies the Augmented Dickey and Fuller [124] test and DF-GLS denotes the Dickey-Fuller Generalized Least Squares test of Elliott et al. [125]. Also, ***, **, * denote significance at the 1%, 5% and the 10% levels respectively.

Table 7
Cointegration findings.

ARDL bound test									
The Statistic		Given 10%		Given 5%		Given 1%		The P-value	
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
F-statistic	7.423***	3.155	4.814	3.907	5.152	4.987	6.825	0.001	0.004
t-statistic	−6.214***	−2.031	−3.772	−3.453	−4.011	−3.974	−5.228	0.004	0.008

Maki cointegration test (trend and regime shifts)			
Model	Test Value	Critical Value (5%)	Break Year
EQI = f(FD, GI, NR, GI*FD, NR*FD, GDP)	−8.457**	−6.624	2010
EQI = f(FD, GI, NR, GI*FD, NR*FD, GDP)	−10.473**	−8.415	2009, 2011
EQI = f(FD, GI, NR, GI*FD, NR*FD, GDP)	−11.234**	−8.754	2008, 2010, 2012
EQI = f(FD, GI, NR, GI*FD, NR*FD, GDP)	−12.157**	−9.524	2007, 2009, 2011, 2013
EQI = f(FD, GI, NR, GI*FD, NR*FD, GDP)	−14.454**	−9.828	2006, 2008, 2010, 2011, 2014

Notes: Bound results also upheld in the Kripfganz and Schneider [107] critical value bounds and approximate p-values ***, ** denote significance (1% and at the 5% considerations).

Table 8
Dynamic ARDL Simulation with EQI as the Response Variable.

Variable	Coefficient	Std. Error	t-Value	Prob.
Long-Run				
LnFD	0.946	0.194	4.87	0.000***
LnGI	−0.775	0.182	−4.26	0.000***
LnNR	1.682	0.297	5.66	0.000***
Ln(GI*FD)	−0.431	0.130	−3.32	0.000***
Ln(NR*FD)	1.598	0.290	5.51	0.000***
LnGDP	0.794	0.183	4.34	0.000***
Short-Run				
ΔLnFD	0.447	0.125	3.58	0.000***
ΔLnGI	−0.291	0.102	−2.84	0.024**
ΔLnNR	0.438	0.130	3.36	0.000***
ΔLn(GI*FD)	−0.257	0.120	−2.15	0.052*
ΔLn (NR*FD)	0.691	0.167	4.13	0.000***
ΔLnGDP	0.144	0.052	2.76	0.033**
ECT	−0.812	0.174	−4.67	0.000***
Diagnostics				
R^2	0.784		White test	0.823 (0.413)
Adjusted R^2	0.752		Jarque-Bera test	1.245 (0.672)
F-statistic	144.116(0.000) ***		Reset test	2.014 (0.724)
LM test	1.105(0.711)		SWALD test	0.857 (0.421)

Note: ***, **, * denote significance at the 1%, 5%, and the 10% levels respectively, values in brackets () denote probabilities.

undertakings. Moreover, the government should support businesses with the necessary funding to innovate and find effectual solutions that could improve their operations. Hongqiao et al. [133] study for the US, and JinRu and Qamruzzaman [134] investigation on G7 economies are in tandem with the above finding. However, Khan et al.' [135] analysis of 176 nations conflicts with the study's outcome.

Also, NR was a significantly positive determinant of Ghana's ecological pollution. We go by the assumption of ceteris paribus, a 1% rise in NR triggered EQI by 1.682% and 0.438%, and this is the case for the long run and the short-run accordingly. This implies natural resource exploitation resulted in disastrous ecological consequences in the nation. Entities operating in the natural resource sector use energy-intensive equipment in their operations. This increases the level of pollutant emissions thereby degrading the environment. The exposition here backs Zakari et al. [136], Khan et al. [137], Onifade et al. [138], and Zakari & Khan [139] that natural resource extraction and processing damages the ecosystem by causing desertification and global warming; harming wildlife; and polluting land, air, and water bodies among others. Gao and Tian [140] also documented natural resource overdependence as a contributing factor to China's ecological deficit. However, in Arslan et al. [141] study on China, natural resources improved ecological quality at the expense of economic development. Also, Miao et al. [47] investigation of newly industrialized economies confirmed natural resources as friendly to environmental safety. Besides, the sign of the interactive term between GI and FD (GI*FD) was negatively significantly applicable under the long-run case as well as for the case of the short-run. This implies that GI and FD jointly promoted environmental sustainability by mitigating pollutant emissions.

Thus, in a nutshell, GI helped to minimize the ecological changes from FD via the lowering of the nation's short-term and long-term pollution rates. It is therefore pertinent for the nation to focus on environmentally related innovations because they do not only curb emissions directly but also minimize them indirectly by greening FD activities in the country. Similarly, the interactive term between NR and FD (NR*FD) positively explained the EQI of the nation. This implies NR and FD jointly promote pollution in the ecosystem. In other words, natural resources enhance the damaging effects of FD on the nation's ecology. This discovery is not surprising because natural resource activities stimulate financial sector development, which has been viewed as an agent of pollutant emissions by researchers.

Also, GDP had a significantly positive effect on EQI. Ceteris paribus, assuming a 1 percentage rise in GDP raised EQI by 0.794% and 0.144% respectively in the long and the short run. This finding implies, that GDP was detrimental to ecological quality in Ghana. The discovery is not surprising because almost all economic activities undertaken in the nation are linked to the utilization of dirty energies that escalate the rate of pollutant emissions, thereby worsening environmental quality. According to Obobisa et al. [67], countries in Africa focus on activities that boost economic development. However, this desire for economic advancement results in the consumption of polluting energies that end up contaminating the environment. Summarily, it can be inferred that the Ghanaian economy grew at the expense of its environment. Also, the long-term detrimental effects of economic progress on the nation's ecology were more than that of the short-term. The studies of Usman and Balsalobre-Lorente [95] for 12 advanced economies and Wang and Huang [142] for East Asian nations offer support to the harmful effects of GDP on the environment. Besides, the ECT value of 0.812 is deemed good firstly being negative and secondly for its statical relevance with the implication that disequilibrium in the short-run was restored to the long-run equilibrium level. Notably, the said correction would be roughly 81.2% yearly. Also, the adjusted R-squared value (0.752) mainly reveals that 75.2% of the total variations in EQI were explained by changes in the explanatory variables. To add to these, the obtained F-

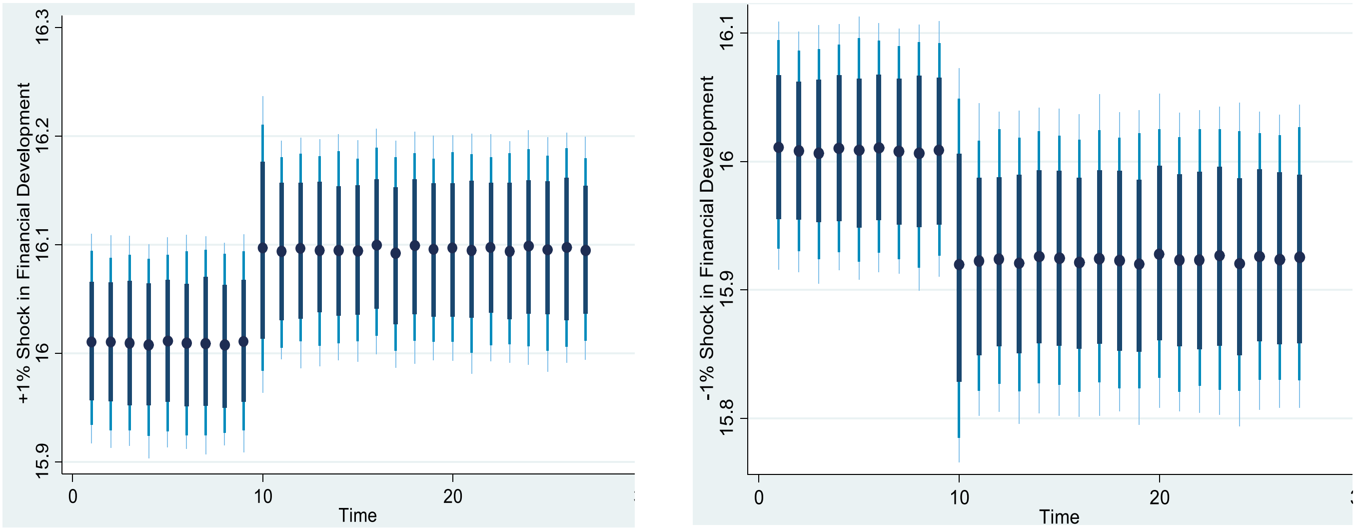

Fig. 2. Positive and negative 1% shock in financial development, here the average estimated values are represented by dots whereas, the lines of blue from thick to lighter parts are for confidence intervals at mainly 75%, 90%, & 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

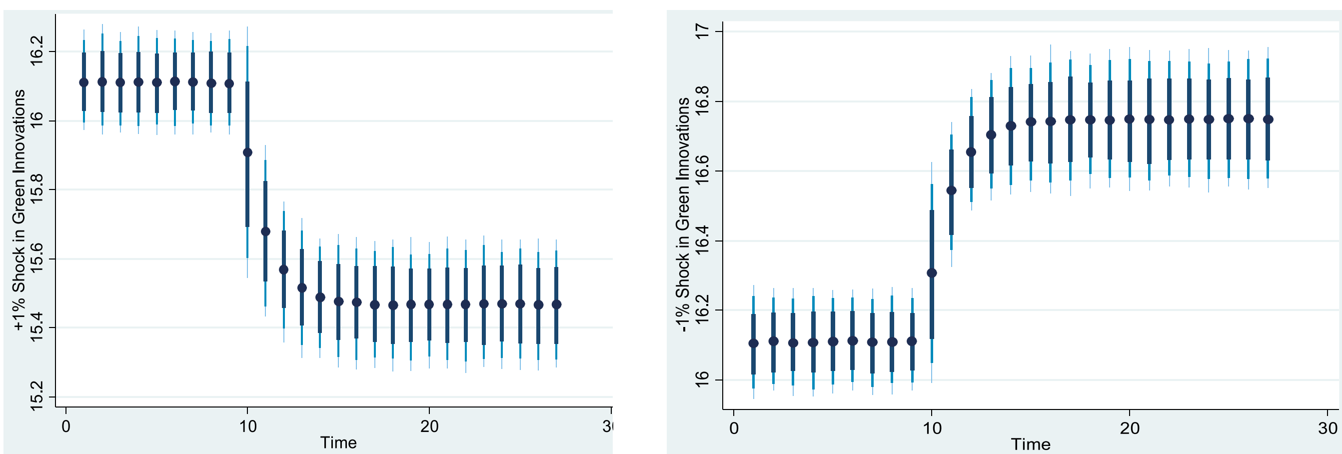

Fig. 3. Positive and negative 1% shock in green innovations, here the average estimated values are represented by dots whereas, the lines of blue from thick to lighter parts are for confidence intervals at mainly 75%, 90%, & 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

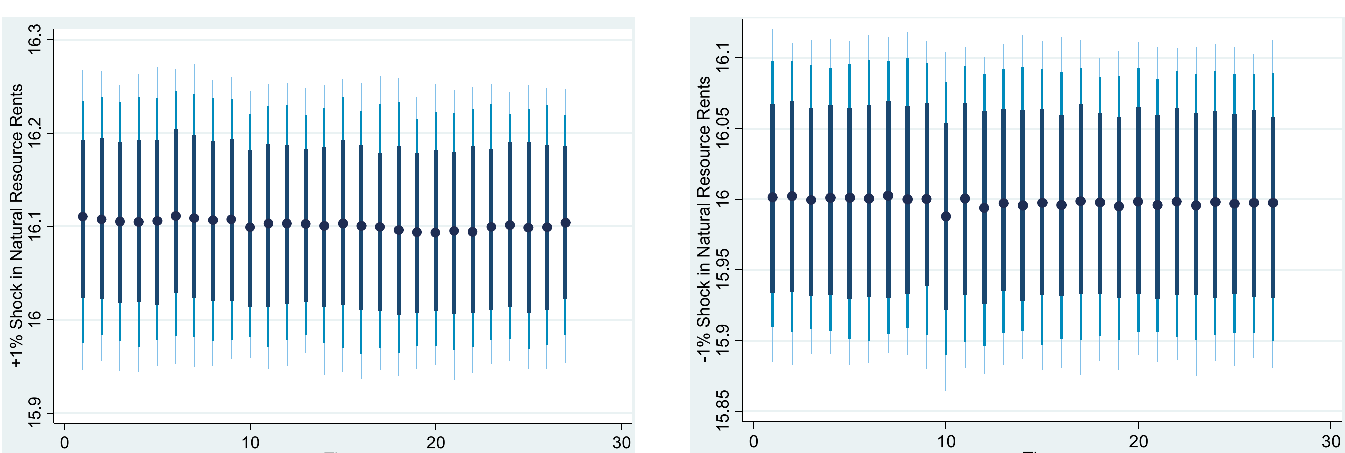

Fig. 4. Positive and negative 1% shock in natural resource rents, here the average estimated values are represented by dots whereas, the lines of blue from thick to lighter parts are for confidence intervals at mainly 75%, 90%, & 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

statistic significantly indicates desirable high predictive power for the whole model. On the diagnostic tests, there was no heteroscedasticity, model misspecification, serial correlation, and structural break concerns. Also, the variables were normally distributed.

Finally, we examined the effects of the factors (explanatory) on the criterion variable, since it is one of the unique pros of the DARDL estimator. These effects cover positive & negative aspects. From Fig. 2, a + 1% change in FD will promote ecological pollution in Ghana, however, a − 1% change in the variable will mitigate pollutant emissions in the nation. This suggests that stimulating developments in the financial sector will damage the country's environmental sustainability, but if developments in the financial sector are curtailed, ecological quality will be enhanced. Also, a + 1% change in GI will reduce pollution in the ecosystem, but a − 1% change in the variable will escalate pollution in the country as shown in Fig. 3. This implies, that intensifying investments in GI will improve the nation's ecological quality, but if investments in GI are minimized, ecological sustainability in the nation will be harmed. Moreover, both positive and negative 1% shock in natural resources will have an immaterial impact on pollutant emissions as portrayed in Fig. 4. This signposts that, the increase or decrease in natural resources will not significantly explain environmental sustainability in the nation. Besides, a + 1% shock in GI*FD will eventually reduce emissions, meanwhile, a − 1% shock in GI*FD will escalate the country's level of emissions as per Fig. 5. This indicates that if the interaction between GI and FD is enhanced, ecological quality will improve, but if the interaction between the variables is minimized, pollution in the ecosystem will be raised. Also, a + 1% change in NR*FD will escalate pollutant emissions in the country, however, a − 1% change in NR*FD will have a trivial effect on pollutant emissions as exhibited in Fig. 6. This signposts that intensifying the interaction between NR and FD will harm environmental sustainability in the nation, however, if the interaction between the variables is minimized, the country's ecosystem will not be materially influenced. Finally, a + 1% shock in GDP will promote emissions in the nation, however, a − 1% shock in the variable will minimize the country's emissions as displayed in Fig. 7. This signifies that if economic development is increased, environmental sustainability in the country will be damaged, however, if economic development is minimized, ecological quality in the nation will be enhanced.

3.2.3.2. Sensitivity analysis. For robustness reasons, we conducted two sensitivity analyses. First, we employed ecological footprint (EF) as a measure of environmental quality to examine whether the choice of models will alter the results. From the results displayed in Table 9, FD was a significantly positive determinant of EF (short run & long run inclusive). Also, NR and GDP positively explained the EF of the nations in the long and the short-run. Besides, the coefficient of GI was negative and statistically significant in both periods. Also, the interactive term between GI and FD negatively determined ecological pollution. Finally, the parameter of the interactive term between NR and FD was a substantially positive predictor of the EF of the country. Summarily, FD, NR, GDP and NR*FD worsened ecological quality by spurring pollutant emissions. However, GI and GI*FD improved environmental sustainability by minimizing the rate of emissions in the nation. These discoveries were consistent with those under the EQI model in terms of the signs of the coefficient estimates. Moreover, the diagnostic tests under the two models were also consistent. Consistency in the outcomes of the two models implies the results were robust. Secondly, the ARDL technique was applied to also compute the EQI model to confirm whether the results remained consistent across different methodologies. Following Table 10's results, the predicted signs of the parameter estimates were the same as those under the principal estimator. Thus, the robustness of our results is justified across an alternative technique.

3.2.4. *Causality analysis*

At the final stage, the causal associations amidst the series were explored via the gradual shift causality technique. From the results displayed in Table 11, a unidirectional causality from FD to EQI was observed. This finding validates the corresponding regression estimates. The discovery implies development in the financial sector promoted pollution in the Ghanian's ecosystem. Going by Wang et al. [85] investigation of N-11 economies and Pata et al. [143] analysis of South Asia conflicts this finding. Also, a causality is evidenced from GI to EQI which certifies the corresponding elasticity estimate. This suggests that the nations' environmental sustainability was dependent on GI. Similarly, a causality from natural resources to ecological pollution was disclosed certifying the corresponding regression estimates. This suggests that overexploitation of natural resources worsened ecological quality in the nation. Emir and Karlilar [144] exploration of Turkey supports this revelation. Besides, the interaction between GI and FD and between NR and FD were mutually related to EQI. This implies the interaction amidst the series caused environmental sustainability in the nation. Finally, a unidirectional causality is evidenced from GDP to EQI validating the corresponding elasticity estimates. This signposts that, ecological quality was conditional on the nation's economic advancement activities.

4. Conclusions and policy implications

Financial development, green innovations, and natural resource rents are key factors that explain the environmental quality of economies. For this purpose, we examined the nexus between financial

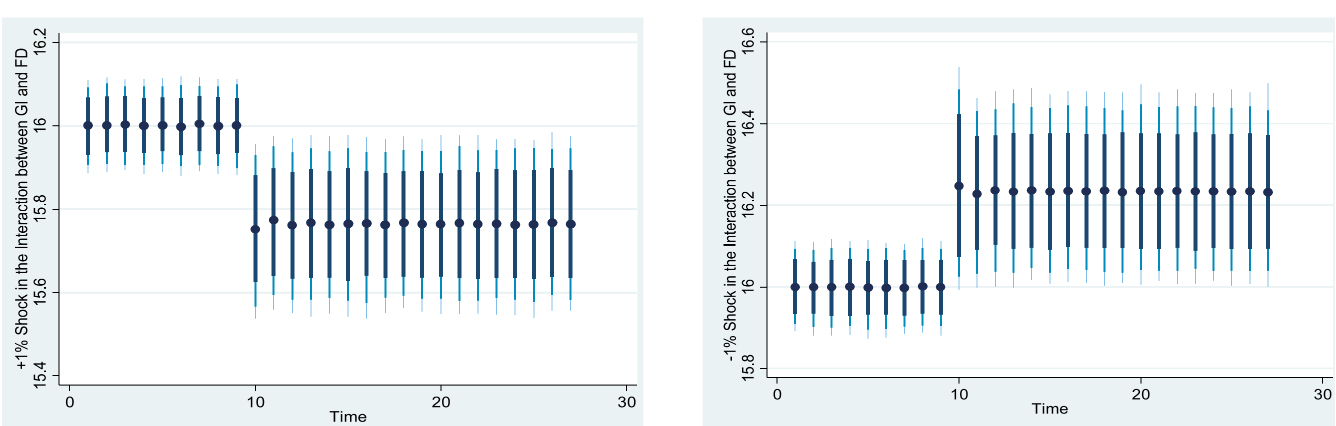

Fig. 5. Positive and negative 1% shock in the interaction between green innovations and financial development, here the average estimated values are represented by dots whereas, the lines of blue from thick to lighter parts are for confidence intervals at mainly 75%, 90%, & 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

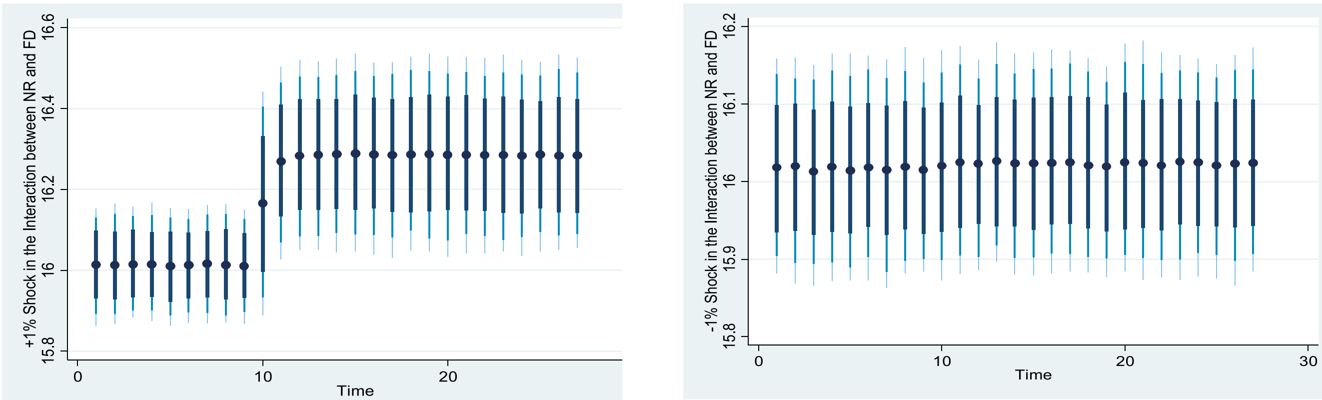

Fig. 6. Positive and negative 1% shock in the interaction between natural resource rents and financial development. Note: The dots denote average predicted values while dark blue to light blue lines represent 75%, 90%, and 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

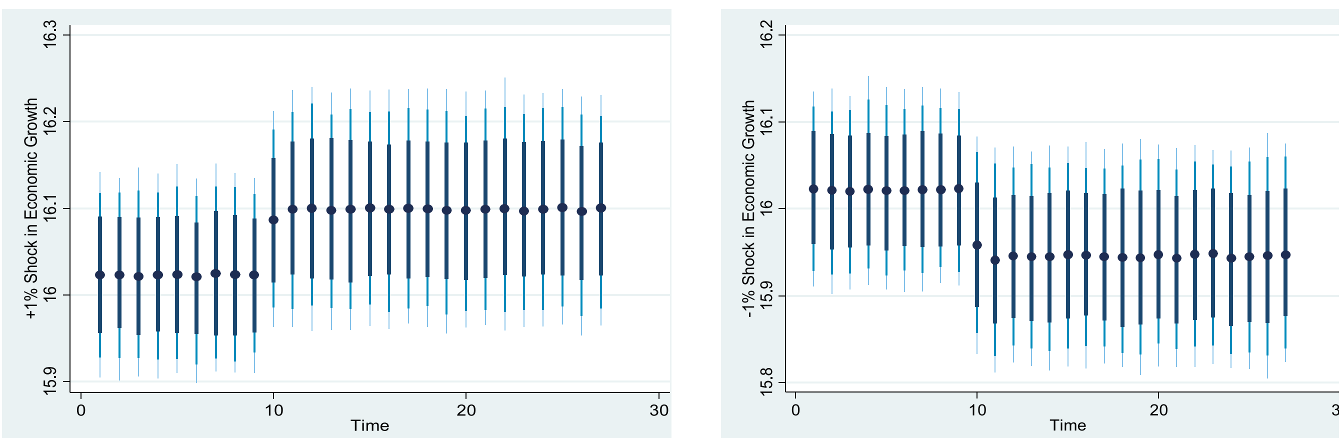

Fig. 7. Positive and negative 1% shock in economic growth, here the average estimated values are represented by dots whereas, the lines of blue from thick to lighter parts are for confidence intervals at mainly 75%, 90%, & 95%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

development and environmental quality in Ghana, while accounting for the moderating roles of green innovations and natural resource rents over the period 1990 to 2018. While financial development, natural resource rents and economic growth were significant positive determinants of pollutant emissions in the Sub-Saharan Ghanian economy, green innovations negatively predicted ecological pollution in the nation. Besides, the interaction between green innovations and financial development improved ecological quality. Additionally, the interactive links between green innovations and financial development were bidirectionally related to the ecological damage.

With reference to the aforestated discoveries, the following policy implications were deduced. First, since development in the financial sector damaged the environment, it is important to emphasize policies to lessen environmental damage by integrating ecological concerns and rules into the supply of financial services for consumption and production activities. Such actions could increase the ability of the financial sector to act as a catalyst for the uptake and financing of innovative pollution mitigation technologies and ecologically harmless projects. Meanwhile, advancing financial development can promote the growth of Ghana's environment in two major pathways. First, it can increase private sector spending on research and development on low-pollution technologies. Second, it can assist in identifying and removing obstacles that impede businesses and households from embracing energies from clean sources. Moreover, green innovations promote environmental sustainability in the country. Therefore, the government should increase investments in ecologically-related technologies. Also, funding for innovative projects should be included in public policies for technologies that could ensure complementarity between high economic expansion and low environmental deterioration. In order to properly address escalating ecological issues, the government must implement green and innovative technologies across all sectors of the economy. Businesses should be aided in their transition from outdated technologies to more innovative and eco-friendly ones.

Furthermore, the interactions between green innovations and financial development improved environmental sustainability, however, the interaction between natural resources and FD isn't quite good for the nation's sustainable ecological expectations. This implies, that increasing investments in green innovations, efficient financial systems, and strengthening of institutions for adequate eco-friendly natural resource control policies could help in minimizing environmental deterioration in the Sub-Saharan Ghanian economy. We thereby further recommend additional research on international financial flows, technological diffusion, and regulatory settings to further strengthen the sustainability capacity of the Sub-Saharan Ghanian economy. Such policy implementations have been argued to be beneficial even in the cases of some top-ten countries with much larger ecological footprints [145].

In a nutshell, economic growth was a significantly positive determinant of pollutant emissions. This implies, that environmental degradation worsened at the phase of economic expansion. Thus, as the

Table 9
Dynamic ARDL simulation with EF as the explained variable.

The Variable	The Coefficient	The Std. Error	The t-Value	The Prob.
For the Long-Run				
LnFD	0.612	0.177	3.46	0.000***
LnGI	−0.456	0.153	−2.98	0.012**
LnNR	0.511	0.123	4.14	0.000***
Ln(GI*FD)	−0.203	0.067	−3.01	0.000***
Ln(NR*FD)	0.484	0.109	4.43	0.000***
LnGDP	0.362	0.120	3.02	0.000***
For the Short-Run				
ΔLnFD	0.374	0.115	3.24	0.000***
ΔLnGI	−0.118	0.057	−2.07	0.075*
ΔLnNR	0.344	0.111	3.11	0.000***
ΔLn(GI*FD)	−0.105	0.052	−2.02	0.084*
ΔLn(NR*FD)	0.214	0.068	3.14	0.000***
ΔLnGDP	0.047	0.020	2.35	0.062*
ECT	−0.755	0.147	−5.15	0.000***
Diagnostics				
R-squared (R^2)	0.744		White test	0.478 (0.551)
Adjusted R^2	0.715		Jarque-Bera test	0.842 (0.841)
F-statistic	112.052(0.000)***		Reset test	1.124 (0.981)
LM test	0.967(0.851)		SWALD test	0.692 (0.644)

Note: ***, **, * denote significance at the 1%, 5%, and the 10% levels respectively, values in brackets () denote probabilities.

Table 10
ARDL estimation with EQI as the dependent variable.

The Variable	The Coefficient	The Std. Error	The t-Value	The Prob.
The Long-Run				
LnFD	0.541	0.155	3.48	0.000***
LnGI	−0.362	0.126	−2.87	0.000***
LnNR	0.417	0.118	3.54	0.000***
Ln(GI*FD)	−0.198	0.101	−1.97	0.054*
Ln(NR*FD)	0.343	0.128	2.67	0.000***
LnGDP	0.236	0.086	2.76	0.000***
The Short-Run				
ΔLnFD	0.315	0.112	2.82	0.000***
ΔLnGI	−0.201	0.095	−2.11	0.022**
ΔLnNR	0.344	0.118	2.91	0.000***
ΔLn(GI*FD)	−0.172	0.089	−1.93	0.064*
ΔLn(NR*FD)	0.228	0.090	2.52	0.000***
ΔLnGDP	0.207	0.088	2.34	0.017**
ECT	−0.712	0.149	−4.78	0.000***
Diagnostics				
R-squared (R^2)	0.732		White test	0.313 (0.428)
Adjusted R^2	0.701		Jarque-Bera test	0.724 (0.514)
F-statistic	98.114(0.000)***		Reset test	1.054 (0.772)
LM test	0.721(0.6143)		SWALD test	0.315 (0.848)

Note: ***, **, * denote significance at the 1%, 5%, and the 10% levels respectively, values in brackets () denote probabilities.

economy enlarged and depended more on filthy fuels, poor ecological conditions started to arise. Therefore, the government should increase its commitment to more sustainable economic production targets. This could be accomplished by including clean energy sources in the nation's sustainable development plans, providing incentives for the utilization of green energies, and making energy efficiency a high priority. The government should also stimulate research and development in environmentally friendly activities as well as innovative economic activities.

Table 11
Gradual shift causality test.

The Causality Path	The Wald-stat	The No. of Fourier	The Prob.	Last Decision
LnFD→LnEQI	14.732	4	0.000***	The H_0 is rejected
LnEQI→LnFD	2.678	4	0.871	The H_0 is valid
LnGI→LnEQI	11.452	4	0.004***	The H_0 is rejected
LnEQI→LnGI	4.201	4	0.567	The H_0 is valid
LnNR→LnEQI	13.575	3	0.000***	The H_0 is rejected
LnEQI→LnNR	3.114	3	0.745	The H_0 is valid
Ln(GI*FD) → LnEQI	11.627	3	0.002***	The H_0 is rejected
LnEQI→ Ln (GI*FD)	9.408	3	0.034**	The H_0 is rejected
Ln(NR*FD) → LnEQI	10.245	2	0.007***	The H_0 is rejected
LnEQI→ Ln (NR*FD)	8.583	2	0.061*	The H_0 is rejected
LnGDP→LnEQI	12.454	2	0.001***	The H_0 is rejected
LnEQI→LnGDP	3.482	2	0.611	The H_0 is valid

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

Summarily, to accomplish the emission mitigation targets of Ghana, reforms that boost regulatory and policymaking capacities are needed. We implore the government to attain a thorough understanding of what makes up a successful emission reduction policy. The government must actively participate in creating and putting into practice effective ecological policies, regulations, and designs. Plans and policies must be implemented with effective governance in order to spur the necessary investment, innovation, and change. Additionally, the government should work together to create practical pollution-preventive legislation and should allocate more resources to innovative technologies.

4.1. Limitation of study

Although the current study has addressed the subject matter of the research with well-informed empirical-based evidence, however, we could not extend the extent of the analysis beyond 2018 due to the scarcity of data beyond that timeframe. Therefore, as data becomes more available, future explorations could examine the topic in detail. The study was also limited to the DARDL and the ARDL techniques. This implies, that care should be taken when interpreting the results because if other econometric methods are considered, the outcome might be different. Moreover, the study was confined to only Ghana. Therefore, caution should be exercised in the generalization of the discoveries.

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Authors' contributions

All authors have jointly contributed to the manuscript.

CRediT authorship contribution statement

Mohammed Musah: Formal analysis, Data curation, Conceptualization. **Stephen Taiwo Onifade:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization. **Isaac Ankrah:** Writing – original draft. **Bright Akwasi Gyamfi:** Formal analysis, Data curation. **George Kofi Amoako:** Writing – original draft.

Declaration of competing interest

The authors wish to disclose here that there are no potential conflicts of interest at any level of this study.

Data availability

The data for this present study are sourced from the Organization for Economic Co-operation and Development – OECD, (https://www.oecd.org/), and the database of the World Bank's World Development Indicators (https://data.worldbank.org).

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