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## Article

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# Quantifying carbon emissions through financial development in Ghana: empirical evidence from novel dynamic ARDL and KRLS techniques

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## ABSTRACT

The critical issue of environmental degradation emphasises the urgent need for coordinated actions to safeguard and restore the planet's fragile ecological balance. This study examines the relationship between financial development and carbon emissions in Ghana from 1990 to 2020, focusing on the roles of natural resource rents and economic sustainability. Utilizing time-series data from the World Bank and applying a dynamic autoregressive distributed lag (ARDL) model and kernel-based regularized least squares (KRLS) machine learning technique, the findings indicate that financial development significantly increases carbon emissions in both the short- and long-term. At the same time, natural resource rents have a negligible impact on emissions in the short term but contribute to increased emissions in the long run. Conversely, economic sustainability consistently reduces carbon emissions in the short- and long-run. Our findings highlight the need for policymakers to prioritize green financing initiatives, promote financial products that support renewable energy, and implement stricter regulations on natural resource exploitation. Additionally, incentives for financial institutions to invest in environmentally-sustainable projects are vital for achieving Ghana's carbon neutrality goals.

## IMPACT STATEMENT

By investigating the interplay between financial development, natural resource rents, and economic sustainability, this study provides critical insights into carbon emissions dynamics within Ghana, underscoring the implications for environmental policy and sustainable economic growth. Employing advanced econometric models, including the ARDL approach and KRLS machine learning technique, the study reveals that financial development contributes to carbon emissions in both the short and long term. At the same time, economic sustainability effectively mitigates emissions across temporal spans. This work is poised to inform policy directions, advocating for an increased emphasis on green financing, promoting environmentally sustainable financial products, and implementing rigorous regulations on natural resource exploitation. By presenting actionable insights for policymakers and financial institutions, this research supports Ghana's objectives for carbon neutrality, contributing to a framework for harmonizing economic development with ecological stewardship and resilience.

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## Introduction

Climate change is a pressing worldwide problem that is of utmost significance and poses a grave danger to the ongoing survival of humankind as it has dire consequences on population health (Prempeh, Frimpong, et al., 2024). The primary catalyst for climate change is the escalating levels of greenhouse gases (GHGs), predominantly carbon emissions (CE). Notwithstanding efforts to reduce CE, worldwide emissions have increased. According to Liu et al. (2024), global CE reached 36.8 million kilotons (kt) in 2023 compared to 35.5 million kilotons(kt) in 2013. The growth in CE is at odds with the Paris

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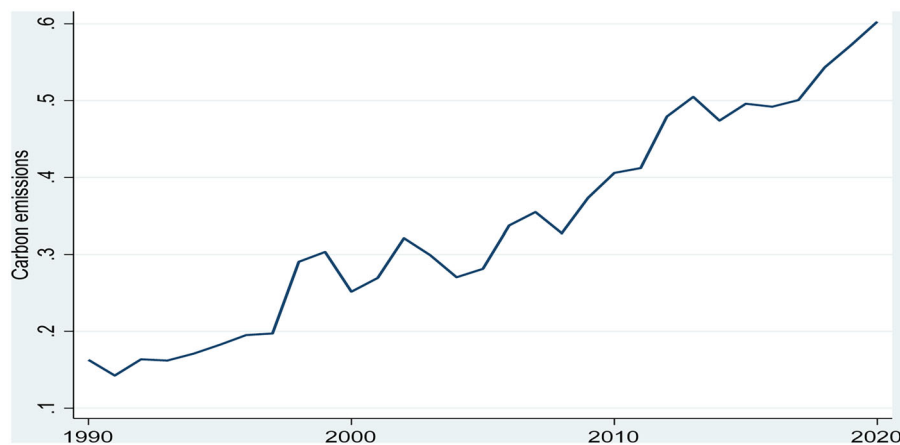
Agreement's goals, which aim to reduce CE and combat climate change. Several economic factors have been highlighted in the literature as significant contributors to CE, including economic growth (EG), exploitation of natural resources, foreign direct investment (FDI), trade openness, energy consumption, industrialisation, financial development (FD), and urbanisation (Luqman, 2024; Mensah & Abdul-Mumuni, 2023; Prempeh, 2024; Wang et al., 2024; Wang et al., 2024a).

EG undoubtedly raises living conditions but hurts the environment (Said, 2024; Slathia et al., 2024; Wang et al., 2023). Building on the findings of Grossman and Krueger (1995), several investigations have explored the association between EG and EC, generally referred to as the Environmental Kuznets Curve (EKC). The EKC hypothesis posits an inverted U-shaped nexus between EG and environmental degradation. Environmental degradation tends to increase in the early stages of EG, but after reaching a specific threshold, further EG leads to environmental improvements. The falling stage of the EKC aligns with economic sustainability (ES). ES is the attainment of enduring economic development via the effective utilisation of resources, the reduction of environmental stresses, and the advancement of social well-being (Bekele et al., 2024). At this stage, nations prioritise the environmental consequences of their activities and hence implement policies and strategies to enhance environmental quality by decreasing CE. Nonetheless, empirical studies on the EKC hypothesis have yielded inconsistent results. Some scholars, such as Xu et al. (2024), Naqvi et al. (2023), and Wang et al. (2023), confirm EKC's existence. On the contrary, Ridwan et al. (2024), Tchapchet (2023), and Halliru et al. (2020) demonstrated that EC continuously rises with EG. Thus, the EKC hypothesis is not supported.

The impact of FD on CE remains contentious in theoretical discourse. Some scholars are of the view that FD helps to mitigate CE by promoting ecologically-friendly investments. For instance, Prempeh (2024) argues that FD may enhance loan accessibility, enabling investments in clean energy technology and energy-efficient projects, ultimately reducing CE. Furthermore, FD can lower CE by promoting capital-intensive renewable energy projects, green technology, and research and development (R&D) initiatives (Wang et al., 2024). In contrast, some academics contend that FD may enhance CE by stimulating the purchase of goods and services. Rising demand for goods and services necessitates more production, which may require intensive energy usage, leading to increases in CE. For example, Habiba et al. (2023) argue that FD fosters increased energy consumption and CE, particularly associated with luxury items that are intensive in energy use. Furthermore, FD may heighten CE by boosting industrialisation and utilisation of energy-intensive equipment (Wang et al., 2024).

Despite natural resource rents (NR) favourable EG effects, its role in mitigating CE remains controversial. Some authors support the opinion that NR promotes environmental quality by mitigating CE. For example, Li et al. (2024) contend that NR promotes environmental quality by reducing CE. Contrarily, other authors claim that NR harms environmental quality by increasing CE. Işık et al. (2024) established that NR heightens CE, supporting the resource curse hypothesis. According to the resource curse hypothesis, civilizations endowed with abundant natural resources may face long-term difficulties maintaining ecological and economic viability. Nations possessing vast natural resources, especially nonrenewable resources such as minerals or oil, often have problems effectively managing their use while minimising environmental impacts. Rapidly pursuing the exploitation of resources may result in negative consequences including deforestation, destruction of habitats, pollution, and a rise in CE. Endowed with abundant natural resources, Ghana is plagued by weak institutional frameworks, corruption, lack of transparency, and the detrimental impact of 'galamsey' activities, aggravating the undesirable outcomes of abundant natural resources.

To date, few studies have explored the impact of FD on CE and provided contradictory findings. While some argue that FD has a beneficial effect, others contend that it has negative consequences, while others claim that there is no link. Several studies focusing on emerging countries and Sub-Saharan Africa have shown a notable adverse impact of FD on CE. See for example, Prempeh et al. (2023), Ashena and Shahpari (2024), and Prempeh (2024). However, some have demonstrated the positive impact of FD on CE, for example, Ali et al. (2019), Rajpurohit and Sharma (2020) and Mukhtarov et al. (2024). Other studies, such as Abokyi et al. (2019), Cosmas et al. (2019) and Khan et al. (2021), among others, revealed no substantial connections between FD and CE. In conclusion, there is limited evidence regarding the impact of FD on CE in Ghana. Given the conflicting findings in the existing literature, this study aims to examine the effects of FD on CE while accounting for variations in NR and ES in Ghana from 1990 to 2020.



**Figure 1.** A plot of CO<sub>2</sub> emissions (metric tons per capita) in Ghana (1990–2020).

This study centres on Ghana due to its status as one of the world's lowest carbon emitters. However, Ghana is grappling with the problem of declining environmental quality due to the escalation of CE, as seen in [Figure 1](#). Ghana generates approximately 66% of its electricity from thermal sources, contributing to its increasing CE. Despite contributing 25.6 million metric tons of CO<sub>2</sub> (Mt CO<sub>2</sub>e), or 0.06% of GHG emissions, Ghana is disproportionately affected by the effects of climate change. The annual cost of environmental deterioration in Ghana is projected to be \$6.3 billion, which accounts for almost 11% of the country's GDP in 2017 (World Bank, 2020). Under its Nationally Determined Contribution (NDC) as part of the Paris Agreement, Ghana has committed to reducing GHG emissions by 15% unconditionally and up to 45% with international support, relative to 2015 levels, by 2030. Prempeh (2023) posits that EG increases environmental deterioration due to FD. The Central Bank of Ghana (BoG) has implemented measures to alleviate environmental deterioration by promoting green investment projects. For example, BoG has signed an agreement with International Finance Corporation (IFC) to promote green financing. As a result, the BoG has introduced the Ghana Sustainable Banking Principles (SBPs) with support from the International Finance Corporation (IFC). In addition, The Ghana Stock Exchange (GSE), in partnership with the Securities and Exchange Commission (SEC), introduced the Green and Sustainable Bond Rules to guide the listing and trading of environmentally friendly and sustainable bonds on the Ghanaian market in 2022, with the backing of IFC. Ghana has seen notable progress in FD. Despite these advancements, Ghana's FD still lags behind developed countries and the global average. As Ghana's financial sector grows, coupled with its heavy reliance on natural resources, it is critical to understand how FD, NR, and ES influence CE. This paper aims to explore the complex short- and long-term relationships among FD, NR, ES, and CE in Ghana to inform climate change policies and promote sustainable development.

Drawing from the evidence and arguments presented, this study makes the following contributions to and expands the literature on FD and CE. First, as far as we are aware, no study has simultaneously incorporated FD, NR, and ES in their model. Therefore, this study evaluates whether FD, NR and ES simultaneously influence CE. Second, this paper introduces the ES into the analysis of CE for Ghana, marking a novel contribution to existing literature. ES implies that an economic system or activity may endure for an extended period without degenerating the environment, society, or future generations. ES is a more comprehensive viewpoint, and economic growth and development are its dimensions (Mehmood & Kaewsang-on, 2024b). Third, in contrast to conventional econometric approaches, the study utilised the novel dynamic ARDL (DYARDL) and kernel-based regularised least squares (KRLS) machine learning algorithm, providing consistent and reliable results. Lastly, Ghana strives to accomplish the eighth and thirteenth Sustainable Development Goals (SDGs). In addition to addressing climate change and its dire effects (SDG 13), the country hopes to advance equitable and sustainable economic growth (SDG 8). Therefore, this study has significant policy ramifications for achieving the relevant SDGs.

We have partitioned the rest of the paper as follows: The literature review and hypotheses development section reviews the pertinent literature and develops hypotheses, whilst the Methodology section is devoted to the methodology. The results and discussion section presents the empirical findings, whilst the Conclusion and policy implications section offers the conclusion and policy implications.

## Literature review and hypotheses development

### *Financial development and CO<sub>2</sub> emissions*

The core principle of FD is to enhance a country's financial system by fostering efficiency, comprehensiveness, and inclusiveness, underpinned by robust institutions, vibrant markets, and prudent regulatory instruments, which drive EG and financial stability through improved resource allocation. According to Chitimira and Warikandwa (2023), adhering to this principle would help achieve the 17 SDGs of the United Nations. The link between FD and CE has not been extensively studied, and what has been done so far offers contradicting theories and empirical findings about how FD influences CE (Kaushal et al., 2024; Said, 2024; Xiufan & Decheng, 2024). From a theoretical perspective, FD can heighten and mitigate CE impacts, as environmental finance theory suggests. The theory suggests that FD can impact CE in two distinct ways, contingent upon the application of financial instruments (Ehigiamusoe et al., 2024). A robust financial system can inadvertently escalate CE by channeling investments into energy-intensive industries, potentially leading to an investment-driven emissions surge (Kaushal et al., 2024; Ul-Haq et al., 2024). Conversely, directing FD towards sustainable investments can mitigate these adverse effects (Li et al., 2024; Prempeh, Kyeremeh, et al., 2024; Zhang et al., 2024). Green financing mechanisms, such as green bonds, have been successfully utilised in financing renewable energy projects, which are pivotal in expediting the shift towards a low-carbon economy (Liu et al., 2024; Zhang et al., 2024).

Empirical research has similarly yielded conflicting results regarding the influence of FD on CE, much like the theoretical ambiguity. For example, Prempeh et al. (2023) explored the effects of FD on CE in 11 ECOWAS economies using the augmented mean group (AMG) estimator and Driscoll-Kraay (D-K) panel regression. The empirical results demonstrated that FD adversely influences CE significantly. Similarly, Prempeh (2024) focused on 10 ECOWAS nations and found that FD substantially dampens CE using the D-K panel and panel quantile regression (PQR) techniques. Later, Ashena and Shahpari (2024) examined the link between FD and CE in 30 developing countries over the period 1990–2018 by using the Panel-ARDL approach. Their empirical outcomes provide compelling evidence of the adverse effect of FD on CE. Mehmood and Kaewsang-on (2024a) also established a negative impact of FD on CE in the top 10 tourist economies using data spanning 1991–2021. Mensah and Abdul-Mumuni (2023) investigated the asymmetric effect of FD on CE using a sample of 31 SSA nations and the panel NARDL approach. The study revealed that both positive and adverse shock in FD hinders CE. Shang et al. (2023), using the ARDL and NARDL approaches, concluded that FD mitigates CE in China in the long term. Omoke et al. (2020) used the NARDL technique and found evidence that positive shock in FD deters CE, while adverse shocks in FD induce CE. Using the three-stage least-square-square (3SLS) approach, Alhassan et al. (2022) revealed a noteworthy inverse correlation between CE and FD in Ghana. Ren et al. (2023) analysed the pooled mean group estimator to investigate the relationship between FD and CE in China. Their study revealed that FD plays a role in reducing CE, suggesting that as financial markets advance and access to financial resources improves, it can lead to more efficient energy use, adoption of cleaner technologies, and overall reductions in CE.

On the other hand, other studies have revealed the positive impact of FD on CE. For instance, Ibrahim and Ajide (2021) point out that FD leads to higher CE in the case of BRICS nations. Additionally, Mukhtarov et al. (2024) assessed the influence of FD on CE in Kazakhstan from 1993 through 2020. The outcomes suggest that FD heightens environmental degradation through CO<sub>2</sub> emissions in Kazakhstan. In particular, they indicate that a 0.17% rise in CE is linked to a 1% rise in FD. Using a sample of southern Asian nations, Wang et al. (2024) report that FD is associated with higher CE. Ibrahim and Vo (2021), relying on a sample of 27 countries from 1991–2014, concluded that FD promotes CE. Habiba et al. (2023) scrutinised the connection between FD and CE using the AMG estimator. The empirical studies demonstrated a positive correlation between FD and CE.

Interestingly, the impact of FD on CE is not always straightforward. A study by Cosmas et al. (2019) examined the relationship between FD and CE from 1981 to 2016 using ARDL analysis. Interestingly, their findings indicated a neutral effect, suggesting that FD neither significantly increased nor decreased CE during the studied period. In the context of Ghana, FD has no significant impact on CE. This finding is particularly noteworthy as it underscores that the influence of FD on CE can vary significantly across different regions and economic contexts, thereby highlighting the importance of localized studies when



formulating policy recommendations. Based on the associations suggested in the literature, we propose the following hypothesis:

**H<sub>1</sub>:** Financial development heightens CO<sub>2</sub> emissions in Ghana.

### ***Natural resource rents and CO<sub>2</sub> emissions***

Over the past few decades, empirical research has extensively explored the association between NR and CE. This association is closely linked to the resource curse hypothesis, which holds that countries with abundant natural resources frequently suffer from adverse economic and environmental consequences due to their heavy reliance on resource extraction (Chen et al., 2024). This suggests that resource-rich countries, especially those heavily dependent on fossil fuels, are susceptible to economic distortions that prioritise immediate financial gains from resource rents at the expense of sustainable development and economic diversification into low-carbon sectors. Such dependency exacerbates economic vulnerabilities and drives higher CE, given the inherently carbon-intensive nature of extractive industries. Moreover, the predominance of NR in these economies can impede diversification efforts and stifle innovation, thereby obstructing the transition towards renewable energy (Boulanouar & Essid, 2023). Numerous contemporary studies have explored the nexus between NR and CE and demonstrate divergent results. Some studies have shown that NR substantially contributes to CO<sub>2</sub> emissions, highlighting the necessity of sustainable resource management (Alhassan & Kwakwa, 2023; Chen et al., 2023; Chen & Chen, 2024; Nwani & Adams, 2021; Zhao et al., 2024). According to Işık et al. (2024), NR promotes environmental degradation by inducing CE in 27 OECD nations. Huang et al. (2023) applied the AMG technique and found that NR heightened CE in BRICS economies. In their paper, Shang et al. (2023), using the System Generalised Method of Moments (SGMM) estimations, demonstrated the inducing effect of NR on CE in 36 economies. Kwakwa et al. (2020) found that NR contributed to CE in Ghana.

On the contrary, some studies revealed the mitigating effects of NR on CE (Chen et al., 2023; Luqman, 2024; Shahbaz et al., 2024). Li et al. (2024) found that NR hinders CE. Tufail et al. (2021), using the CS-ARDL model, found that NR dampens CE in OECD economies. A recent study by Wang et al. (2024b) showed that NR has a neutral impact on CE. The neutral effect of NR on CE is supported by Befeke et al. (2023). In the same vein, utilising the moment quantile regression (MMQR) technique, Khaddage-Soboh et al. (2023) determined that lower quantiles have a negative and substantial relation between NR and CE. However, this connection turns positive and statistically insignificant at upper quantiles. Based on the synthesized evidence presented, we propose the second hypothesis:

**H<sub>2</sub>:** Natural resource rents amplify CO<sub>2</sub> emissions.

### ***Economic sustainability and CO<sub>2</sub> emissions***

Exploring the connection between ES and CE is crucial, as it offers policymakers valuable insights for advancing the SDGs, particularly Goals 8 and 13, which focus on promoting inclusive and sustainable economic growth (SDG 8) whilst tackling climate change and its severe impacts (SDG 13). The Environmental Kuznets Curve (EKC) hypothesis, which holds that EG influences CE via a dynamic link characterised by an inverted U-shape, adequately clarifies the impacts of ES on CE. In the early stages of EG, increased industrial activity, heightened energy consumption, and reliance on carbon-intensive technologies promotes CE, signifying a phase where EG occurs at the expense of environmental quality (Ma et al., 2024; Ridwan et al., 2024). As economies advance and reach higher income levels, a gradual shift towards ES is marked by adopting cleaner technologies, enhanced energy efficiency, and enforcing robust environmental regulations (Bekele et al., 2024; Zhong & Ma, 2024). This transition is propelled by heightened public demand for improved environmental standards, increased investments in green technologies, and the implementation of policies aimed at sustainable development.

Consequently, CE begins to decline as societies emphasise long-term environmental well-being in tandem with economic prosperity, illustrating a decoupling of EG from ecological degradation (Xie &

Huang, 2024). Thus, the EKC hypothesis suggests that fostering ES can ultimately lead to a reduction in CE. Since the mid-1990s, researchers have empirically examined the connection between EG and environmental impact, following Grossman and Krueger's (1995) findings that EG initially worsens the environment but improves it after reaching a certain level. Despite this foundational work, subsequent studies have reported varied and conflicting outcomes regarding the growth-environment link. For instance, Li et al. (2024) test the validity of the EKC hypothesis using a sample of 38 countries covering 2002 to 2020. The results in the region validate the EKC hypothesis. In the context of Sub-Saharan Africa, Aminu et al. (2023) validated the EKC hypothesis for the area.

Similarly, Sun et al. (2024) also validated the EKC hypothesis for China from 1985 to 2018. Similar results are also found in empirical studies such as Xu et al. (2024), Naqvi et al. (2023), and Wang et al. (2023). In contrast, in a South Asian study on the EKC hypothesis, Ridwan et al. (2024) found no evidence in favour of the EKC hypothesis in the region. Tchapchet (2023) demonstrates that the EKC is invalid using data from 22 Nordic and non-Nordic European economies from 2005 to 2019. Halliru et al. (2020) failed to establish the EKC hypothesis for West Africa.

In recent years, scholarly interest in determinants of ES has increased due to its potential for advancing environmental quality through impeding CE (Amaliah et al., 2024; Bekele et al., 2024; Cao et al., 2024; Subhan et al., 2024). However, only a few studies have explored how ES influences CE. For example, Mehmood and Kaewsaeng-on (2024b), using the FMOLS, DOLS and PQR techniques, found that ES is a barrier to CE in 10 newly industrialised economies. The empirical outcomes of Zhang et al. (2022) demonstrate that sustainable ecological laws have a suppressive effect on CE in China. Based on the associations suggested in the literature, we propose the following hypothesis:

**H<sub>3</sub>:** Economic sustainability mitigates CO<sub>2</sub> emissions.

The literature shows that the impact of FD, NR, and ES on CE varies based on factors such as the study period, FD level, variables considered, or econometric strategies employed. To the authors' knowledge, no existing studies have explored this relationship in the context of Ghana. Over the past two decades, Ghana has seen improvements in FD, ES, and NR, making examining this association worthwhile as it offers valuable insights. Furthermore, while several studies have focused on EG to explain CE and environmental issues within the EKC framework, it is crucial to address ES, which has been largely overlooked in the literature, except for the recent panel study by Mehmood and Kaewsaeng-on (2024b). To fill this gap, this study investigates how ES influences CE in Ghana, aligning with the declining phase of the inverted U-shaped EKC hypothesis.

## Methodology

### Data description

The current study explores how FD, NR and ES influence CE in Ghana. The study utilised time-series data from 1990 to 2020, mainly attributed to reliable data availability for all key variables. During this period, Ghana implemented various policies to enhance the financial sector while mitigating pollution and addressing the environmental consequences of economic growth. The timeframe is particularly suitable for evaluating these initiatives' long-term effectiveness and gathering reliable data on financial trends and environmental changes. Additionally, this period coincides with heightened global awareness and efforts regarding climate change, including Ghana's ratification of the UN Framework Convention on Climate Change (UNFCCC) in 1995 and its subsequent commitment to the Paris Agreement. Therefore, the period 1990 to 2020 offers a comprehensive context for examining the interrelationships among FD, ES, NR, and CE. The operationalisation of variables, acronyms and their corresponding data sources, informed by a thorough review of pertinent literature, are presented in Table 1. The functional form of the model is presented in Equation (1):

$$CE = f(FD, NR, ES) \quad (1)$$

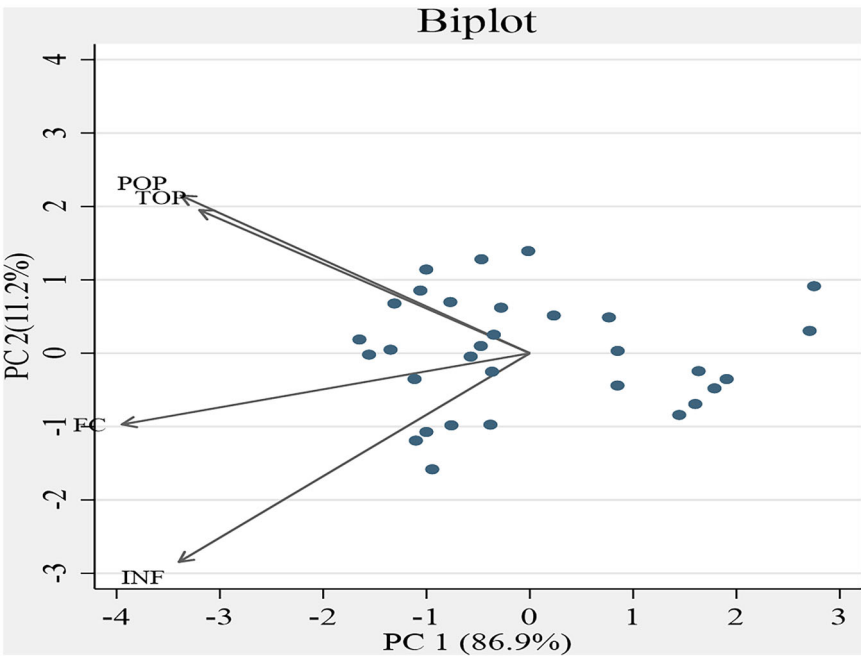


**Table 1.** Variables and data sources.

Variable	Notation	Measure	Data source
Carbon emissions	CE	CO <sub>2</sub> emissions (metric tons per capita)	WDI
Financial development	FD	Domestic credit to private sector (% of GDP)	WDI
Natural resource rent	NR	Total natural resources rents (% of GDP)	WDI
Economic sustainability (PCA)	ES	Trade (% of GDP)	WDI
		Population growth (annual %)	WDI
		Final consumption expenditure (current US\$)	WDI
		Inflation, consumer prices (annual %)	WDI

**Table 2.** Principal component analysis.

Component	Eigenvalue	Proportion	Cumulative
1	3.47747	86.94%	86.94%
2	0.455344	11.38%	98.32%
3	0.06625	1.66%	99.98%
4	0.000939	0.02%	100%



**Figure 2.** Biplot of principal component analysis.

CO<sub>2</sub> emissions per capita (CE) measured in tons is a widely utilised indicator of a country's or region's carbon footprint. It is estimated by dividing the total CO<sub>2</sub> emissions from various sectors, including energy production, industrial processes, transportation, and agriculture, by the total population. The ratio of domestic credit to the private sector to GDP, expressed as a percentage, is commonly utilised as a gauge of FD. This indicator quantifies the proportion of credit allocated by financial institutions to the private sector relative to the nation's total economic output. Total natural resources rents (% of GDP) is a macroeconomic indicator representing the percentage of a country's GDP derived from the extraction and sale of natural resources, such as fossil fuels, minerals, timber, and fisheries. The Economic Sustainability (ES) index is a PCA-derived metric that evaluates a country's capacity to sustain its economy and population in the long term without compromising its natural resources or environmental integrity. The ES index is constructed from a set of indicators, including population, inflation, final consumption expenditure, and trade (P-I-F-T), building on the conceptual framework proposed by Mehmood and Kaewsaeng-on (2024). The PCA outcomes are summarised in Table 2, with the Biplot visualisation presented in Figure 2. The eigenvalues reveal the variance explained by each component, with PC 1 chosen due to its eigenvalue of 3.477, representing 86.94% of the total variance. To standardise the time-series data, improve estimate reliability, and enable elasticity interpretation, all variables except the ES index were log-transformed (*ln*).

## Econometric modelling

This study employs the novel Dynamic Autoregressive Distributed Lag (DYARDL) approach introduced by Jordan and Philips (2018) to investigate the dynamic associations between FD, NR, ES, and CE. The DYARDL technique has gained prominence due to its ability to estimate both long-run and short-run associations between variables and generate impulse response functions that visualise the dynamic responses of variables to positive and negative shocks. Several issues, such as multiple lags, lagging effects, and data anomalies, limit the ARDL model in error correction mode (ECM) and make it challenging to analyse the short- and long-term effects of independent variable shifts. In contrast, the DYARDL technique resolves these limitations. The key advantage of DYARDL lies in its flexibility, as it accommodates both  $I(0)$  and  $I(1)$  variables without requiring prior differencing, unlike stricter cointegration methods such as Engle-Granger or Johansen. Additionally, DYARDL performs well with small sample sizes, whereas other techniques like VAR or GMM may produce biased or inefficient results. However, before executing the DYARDL simulations, it is essential to check the proper order of integration by carrying unit root checks since this econometric approach is founded on the premise that no series is  $I(2)$ . Considering this, we utilize the conventional unit root checks of Phillips-Perron (PP) and Augmented Dickey-Fuller (ADF). We began by determining the unit root properties of every variable before moving on to the linear cointegration test.

The cointegration ARDL bound test, as proposed by Pesaran et al. (2001), is used in this study. This allows for variables with disparate integration, such as  $I(0)$  and  $I(1)$ . This distinctive feature sets the ARDL approach apart from the traditional cointegration tests. Like the DYARDL technique, the ARDL method is also well-suited for small sample settings, as it alleviates biases and yields reliable results. Moreover, the ARDL model guarantees concurrently estimating long-term and short-term parameters. It is a reliable and effective method for analysing long-term relationships and drawing significant policy conclusions from empirical data. The ARDL bounds test for cointegration is represented in Equation (2) as:

$$\begin{aligned} \Delta \ln CE_t = & \Phi_0 + \Phi_1 \ln CE_{t-1} + \Phi_2 (\ln FD)_{t-1} + \Phi_3 (\ln NR)_{t-1} + \Phi_4 (ES)_{t-1} + \sum_{i=1}^r \psi_1 \Delta \ln CE_{t-i} + \sum_{i=1}^r \psi_2 \Delta \ln FD_{t-i} \\ & + \sum_{i=1}^r \psi_3 \Delta \ln NR_{t-i} + \sum_{i=1}^r \psi_4 \Delta ES_{t-i} + \mu_t \end{aligned} \quad (2)$$

In Equation (2), the coefficients of the long-term and short-term parameters are symbolised by  $\Phi_1$  to  $\Phi_4$  and  $\psi_1$  to  $\psi_4$ , respectively. The first difference operator is denoted by  $\Delta$ , and  $r$  signifies the maximum lag length. To ensure a well-specified model, the optimal lag length is selected using appropriate information criteria, thereby eliminating issues of serial correlation, non-normality, heteroscedasticity, and model misspecification in the residual term  $\mu$ . The bound testing technique requires constructing a hypothesis test to investigate the presence of a long-run equilibrium relationship between the variables of interest. The test entails comparing the null hypothesis of no cointegration ( $\Phi_1 = \Phi_2 = \Phi_3 = \Phi_4 = 0$ ) against the alternative hypothesis of the existence of cointegration ( $\Phi_1 \neq \Phi_2 \neq \Phi_3 \neq \Phi_4 \neq 0$ ), allowing for determining whether a significant long-run association is present between the variables. The  $F$ -statistics determine whether the null hypothesis should be accepted or rejected. As posited by Pesaran et al. (2001), cointegration exists among the variables if the estimated  $F$ -statistic surpasses the  $I(1)$  bound. An  $F$ -statistic value below the lower bound corresponding to  $I(0)$  processes suggests a lack of cointegration. It is essential to note that the test result is considered ambiguous when the  $F$ -statistic falls within the  $I(0)$  and  $I(1)$  bounds, precluding a definitive conclusion regarding cointegration.

The long- and short-term parameters were derived in this work using the novel DYARDL simulation approach. This approach boasts advanced capabilities, including estimating, simulation, and graphical visualisation of forecasted outcomes. It also facilitates examining hypothetical changes in a sole predictor variable and its subsequent impact on the outcome variable, *ceteris paribus* (Jordan & Philips, 2018). The methodology requires the series to exhibit a maximum level of integration of order 1, implying that the series must be  $I(0)$  or  $I(1)$  but must not be  $I(2)$ . The study employed a simulation approach involving 5000 replications within the DYARDL error correction term framework to estimate the parameter vector of a multivariate gaussian distribution. Equation (3) illustrates the DYARDL simulation in its error correction representation, which is given by:

$$\Delta \ln CE_t = \Phi_0 + \Psi_0(\ln CE_{t-1}) + \varphi_1 \Delta(\ln FD_t) + \Psi_1(\ln FD_{t-1}) + \varphi_2 \Delta(\ln NR_t) + \Psi_2(\ln NR_{t-1}) + \varphi_3 \Delta(ES_t) + \Psi_2(ES_{t-1}) + \varsigma ECT_{t-1} + \varepsilon_t \quad (3)$$

The acronym  $ECT_{t-1}$  denotes error correction term. Furthermore, the character  $\varsigma$  demotes the estimated value of the ECT, which is expected to be negative and statistically significant. The long-term coefficients are denoted by  $\Psi_1$  to  $\Psi_3$  and the short-term coefficients denoted by  $\varphi_1$  to  $\varphi_3$ . The residual term represented by  $\varepsilon_t$  captures the random fluctuations in the model. In addition, we explore the validity and reliability of the model by executing model diagnostic tests, including Cameron and Trivedi's (White's test) test for heteroscedasticity, the skewness/kurtosis tests for normality, Breusch–Godfrey Lagrange multiplier (LM) test for serial correlation and the Cumulative sum (CUSUM) test by executing recursive and OLS CUSUM plots for parameter steadiness of the model. The causal associations were further examined using the Kernel-based regularised least squares (KRLS) machine learning algorithm, as delineated in the works of Ferwerda et al. (2017). The KRLS model is a nonparametric regression technique that combines the flexibility of kernel methods with the regularization properties of ridge regression. This approach allows for estimating nonlinear connections between the dependent and independent variables. The KRLS model is expressed as:

$$\ln CE = K(K + \gamma I)^{-1} \ln CE \quad (4)$$

Where  $\ln CE$  is the vector of the CE data,  $K$  is the kernel matrix, which captures the similarities between different combinations of  $\ln FD$ ,  $\ln NR$  and  $ES$ . Specifically, each element  $K_{ij} = K((\ln FD_i, \ln NR_i, ES_i), (\ln FD_j, \ln NR_j, ES_j))$  captures the similarity between two different observations.  $\gamma$  is the regularization parameter that prevents overfitting, and  $I$  is the identity matrix. The  $K$  kernel function is chosen as a Gaussian kernel, which is well-suited for capturing the nonlinear interactions between financial development, natural resources, and energy structure. The Gaussian kernel's ability to model complex relationships with high flexibility makes it an ideal choice for this analysis, ensuring that the KRLS model can accurately predict carbon emissions based on the intricate dynamics of the independent variables.

## Results and discussion

Preliminary to model estimation, an extensive empirical analysis of the series was conducted, with a summary of the key statistics presented in Table 3. The results show that the mean values for  $\ln CE$ ,  $\ln FD$ ,  $\ln NR$ , and  $ES$  are -1.165, 2.399, 2.372, and 0.001, respectively. An analysis of the standard deviations reveals that  $ES$  exhibits the highest volatility, followed by  $\ln FD$ ,  $\ln CE$ , and  $\ln NR$ . The skewness coefficients indicate that all variables exhibit negative asymmetry. Moreover, the Jarque-Bera test results confirm that the prediction errors of all variables conform to a gaussian distribution. At the same time, the kurtosis measures reveal that all variables exhibit platykurtic characteristics, indicating a relatively flat distribution with thinner tails.

As indicated by Pesaran et al. (2001) and Jordan and Philips (2018), including  $I(2)$  variables may lead to biased estimates. Hence, evaluating the order of integration of the variables to be included in the mode is essential. Table 4 displays the unit root analysis of each distinct variable using the ADF and PP tests. The outcome suggests that all variables are stationary at the first difference  $I(1)$ . Therefore, the assumption of not including  $I(2)$  variables has not been violated.

The Autoregressive Distributed Lag (ARDL) technique tolerates the specification of distinct lag intervals for the predictor and outcome variables. Table 5 shows the outputs of the numerous methods

**Table 3.** Descriptive statistics and correlation matrix.

Variables	$\ln CE$	$\ln FD$	$\ln NR$	$ES$
Mean	-1.165	2.399	2.372	0.001
Median	-1.135	2.569	2.381	0.126
Maximum	-0.506	2.894	2.777	2.606
Minimum	-1.949	1.297	1.855	-2.921
Std. Dev.	0.433	0.483	0.248	1.419
Skewness	-0.252	-0.955	-0.262	-0.297
Kurtosis	1.876	2.492	2.233	2.559
Jarque-Bera	1.961	5.042	1.114	0.708
Probability	0.375	0.080	0.573	0.702

**Table 4.** Unit root analysis.

Variables	ADF test T-statistic	PP test T-statistic
<i>lnCE</i>	−0.763	−0.191
<i>lnFD</i>	−2.067	−1.704
<i>lnNR</i>	−1.153	−1.119
<i>ES</i>	−0.494	−0.470
$\Delta \ln CE$	−6.707***	−9.484***
$\Delta \ln FD$	−7.712***	−7.341***
$\Delta \ln NR$	−6.572***	−6.573***
$\Delta ES$	−5.645***	−6.687***

Note. \*\*\* denotes significance at 1% level.

**Table 5.** Lag selection test.

Lag	Information criteria					
	LogL	LR	FPE	AIC	SC	HQ
0	−28.950	NA	0.0001	2.354	2.544	2.412
1	38.580	110.942*	3.17e−06*	−1.327*	−0.376*	−1.036*
2	47.807	12.522	5.56E−06	−0.843	0.869	−0.320
3	70.149	23.938	4.37E−06	−1.296	1.178	−0.540

Note. \*Denotes the lag order chosen by the criteria.

**Table 6.** Test for cointegration.

Test statistics	Value	10%		5%		1%		<i>p</i> -value	
		<i>I</i> (0)	<i>I</i> (1)	<i>I</i> (0)	<i>I</i> (1)	<i>I</i> (0)	<i>I</i> (1)	<i>I</i> (0)	<i>I</i> (1)
F-statistics	6.518**	2.677	3.667	3.276	4.412	4.757	6.243	0.002	0.008
t-statistics	−4.657**	−2.565	−3.461	−2.933	−3.885	−3.699	−4.76	0.001	0.012

Note. *I*(0) and *I*(1) are critical values for significance levels of 10%, 5%, and 1%. *P*-value shows critical and approximate *p*-values (Kripfganz & Schneider, 2020). \*\*denotes significance at a 5% level.

employed in determining the optimal lag length. The optimal lag length for our model was selected based on the Akaike Information Criterion (AIC), which revealed that a lag length of 1 yielded the minimum AIC value, indicating that a lag interval of 1 is the most suitable for capturing the dynamic interactions among the selected variables. This outcome is corroborated by the results of the Likelihood Ratio (LR), Final Prediction Error (FPE), Schwarz Criterion (SC), and Hannan-Quinn (HQ) information criteria. The optimal lag length of 1 ensures a parsimonious model specification, minimising the risk of overfitting and enhancing the reliability of the estimates.

The cointegration test results are shown in Table 6, where they indicate a long-term relationship between *lnCE* and its determinants. A meticulous examination of the model suggests that the *F*- and *t*-statistics exceed their corresponding *I*(1) bound critical values, as proposed by Kripfganz and Schneider (2020), at a 5% significance level. Kripfganz and Schneider's (2020) linear regression model offers a dependable critical value for the bounds test, particularly for small sample sizes. The established cointegration provides a robust foundation for quantifying long-term and short-term impacts using the innovative DYARDL simulation approach.

The estimates' robustness is guaranteed by utilising both the ARDL and DYARDL models to quantify the impact of *lnFD*, *lnNR*, and *ES* on *lnCE* in this paper. Tables 7 and 8 display the outcomes of the ARDL and DYARDL correspondingly. The outcomes of both techniques are consistent regarding the direction of the coefficients, but the magnitude of the impacts differ. The result of the DYARDL is presented in Table 8. Over time, the variables return to their long-run equilibrium. The statistically significant negative error correction term (ECT) of −0.67 suggests a 67% rate of adjustment toward this equilibrium. The DYARDL technique is distinguished by its capacity to accurately assess the direction, magnitude, and short- and long-term dynamics of the relationships under investigation.

The findings indicate that *lnFD* substantially increases *lnCE* in the short- and long-term, confirming *H*<sub>1</sub>. The results show that a rise of 1% in *lnFD* causes a short-term increase in *lnCE* of 0.261% and a long-term increase in *lnCE* of 0.61%. The beneficial interaction between *lnFD* and *lnCE* in Ghana can be ascribed to a multifaceted array of factors, encompassing heightened economic activity, investments in

**Table 7.** ARDL estimates.

Variable	Coefficient	Standard error	p-value
<i>Short-run</i>			
$\Delta \ln FD$	0.262***	0.086	0.005
$\Delta \ln NR$	-0.164**	0.076	0.042
$\Delta ES$	-0.106***	0.033	0.001
<i>Long-run</i>			
$\ln FD$	0.614***	0.056	0.000
$\ln NR$	0.255*	0.128	0.059
$ES$	-0.149***	0.020	0.000
Constant	-2.184***	0.467	0.000
$ECT_{-1}$	-0.679***	0.146	0.000
$R^2$	0.573		
Adjusted $R^2$	0.462		
Root MSE	0.080		
N	30		

Note. \*\*\* and \*\* denote significance at 1% and 5% level, respectively.

**Table 8.** Dynamic ARDL estimates.

Variable	Coefficient	Standard error	p-value
<i>Short-run</i>			
$\Delta \ln FD$	0.261**	0.101	0.017
$\Delta \ln NR$	-0.014	0.095	0.888
$\Delta ES$	-0.103***	0.029	0.002
<i>Long-run</i>			
$\ln FD$	0.412***	0.118	0.002
$\ln NR$	0.173**	0.085	0.053
$ES$	-0.100***	0.026	0.001
Constant	-2.164***	0.519	0.000
$ECT_{-1}$	-0.671***	0.169	0.001
$R^2$	0.574		
Adjusted $R^2$	0.438		
$F(7,22)$	4.23		0.004
Root MSE	0.081		
N	30		
Simulations	5000		

Note. \*\*\* and \*\* denote significance at 1% and 5% level, respectively.

carbon-intensive industries, and shifts in consumption patterns, culminating in elevated energy consumption and CE. As the findings demonstrate, FD is associated with an increase in CE in Ghana in the short term. This immediate effect can be attributed to the swift mobilization of financial resources into energy-intensive sectors such as manufacturing, construction, and transportation. The surge in economic activity resulting from improved access to capital drives energy consumption upward, leading to higher CE. In developing economies like Ghana, the absence of immediate integration of green technologies or sustainable financing practices means that FD, at its inception, often prioritizes EG over environmental sustainability. In the long term, the magnitude of the impact increases, indicating a sustained and even more significant impact on CE. This long-term effect highlights financial institutions' pivotal role in shaping economic growth trajectories. Without a shift towards green financing policies, FD continues to bolster industries that significantly contribute to elevated CE levels. However, there exists potential for this relationship to transform over time. With the advent of sustainable banking principles and green bonds, such as those established by Ghana's Sustainable Banking Principles and the Green Bond framework, FD may increasingly facilitate green investments. This evolution could contribute to CE reduction and support Ghana's carbon neutrality objectives.

These findings support the environmental finance theory, emphasising the need for integrated ecological considerations in financial decision-making to mitigate negative impacts and highlighting the importance of sustainable finance practices to reduce the environmental footprint of financial activity. Also, it can be argued that the underdeveloped nature of the Ghanaian financial sector makes it difficult to channel funds towards green (i.e., renewable) projects, which require huge investments at the initial stages (Prempeh, 2023). This finding challenges the works of Mehmood and Kaewsaeng-on (2024a), Prempeh et al. (2023 and 2024), which conclude that  $\ln FD$  mitigates  $\ln CE$ . This discovery further contradicts studies conducted by Abokyi et al. (2019) and Alhassan et al. (2022) in the context of Ghana. The

discrepancy in the results might be ascribed to the control variables utilised, the measurement of variables, the time frame of the study, or the econometric methodologies applied. However, the present finding is analogous to the findings of Ibrahim and Vo (2021), Samour et al. (2022) and Habiba et al. (2023), which endorse that increases in  $\ln CE$  are associated with rises in  $\ln FD$ .

The empirical analysis reveals a dynamic relationship between  $\ln NR$  and  $\ln CE$ , characterized by a negligible and negative short-run effect that turns into a positive and statistically significant long-run effect. The findings specifically show that, at the 5% significance level, an increase of 1% in  $\ln NR$  corresponds to a rise of 0.17% in  $\ln CE$ , confirming hypothesis 2 ( $H_2$ ). These findings further suggest a complex and time-varying connection between  $\ln CE$  and  $\ln NR$ . In the short run, the negative effect, although negligible, may result from the initial investments in clean technologies or more efficient extraction processes, particularly in sectors such as oil, mining, and timber, which might give the impression of reducing CE. For instance, Ghana's mining industry may implement advanced practices that temporarily mitigate the environmental impact of resource extraction, masking the true extent of CE. However, in the long term, as natural resource extraction reaches full capacity and becomes a dominant driver of EG, the environmental costs become more pronounced. This is particularly evident in Ghana's extensive reliance on extractive industries such as gold mining and oil production. Over time, these activities have increased energy consumption and higher CE, reinforcing a positive long-term association between NR and CE. The persistence of illegal mining activities ('*galamsey*'), deforestation, and unsustainable land use further exacerbate this issue. This long-term pattern aligns with the *resource curse phenomenon*, where countries like Ghana, rich in natural resources, often experience long-term environmental degradation. Despite short-term economic gains, the nation's over-reliance on resource extraction perpetuates a cycle of environmental harm, as weak institutional frameworks and insufficient environmental regulations fail to curb the negative impacts. As a result, significant environmental costs offset natural resource abundance, ultimately leading to economic benefits. This discovery is consistent with the conclusions that were drawn by Kwakwa et al. (2020), Huang et al. (2023), Shang et al. (2023) and Lin et al. (2024) but deviates from the findings of Tufail et al. (2021) and Li et al. (2024). Extraction of natural resources often necessitates high energy-consuming procedures that lead to environmental deterioration due to increased CE.

Furthermore, the income derived from the exploitation of natural resources may inadvertently support energy-intensive industries, which support carbon-intensive economic activities. The usage of hazardous chemicals such as cyanide and Mercury in mining operations in Ghana has been mentioned in the media throughout the years. The rise in CE and decline in the quantity and quality of Ghana's cocoa production may be attributed to the increase in irresponsible mining, activities of illicit mining, and deforestation (Alhassan & Kwakwa, 2023). Although Ghana has seen some financial benefits from its natural resources, the findings indicate that the government may have been unable to effectively address the environmental problems caused by mining these resources in the nation. Unsurprisingly, CE is increasing with Ghana's exploitation of natural resources.

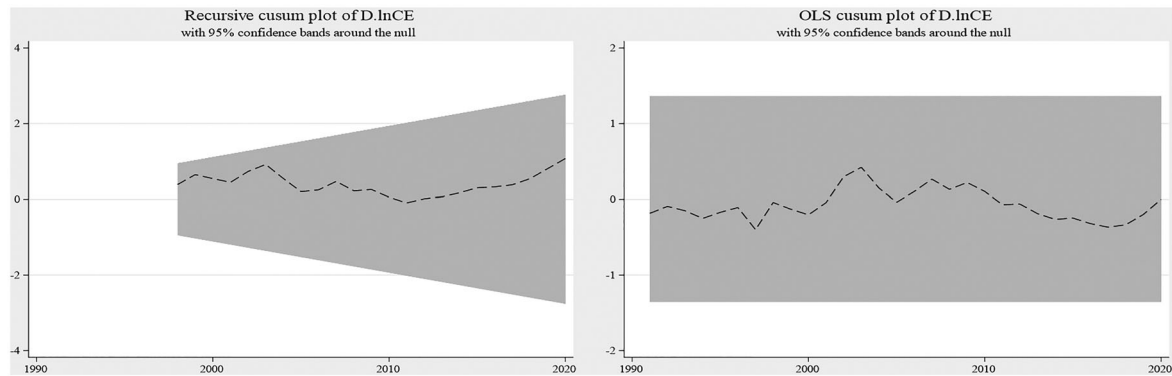
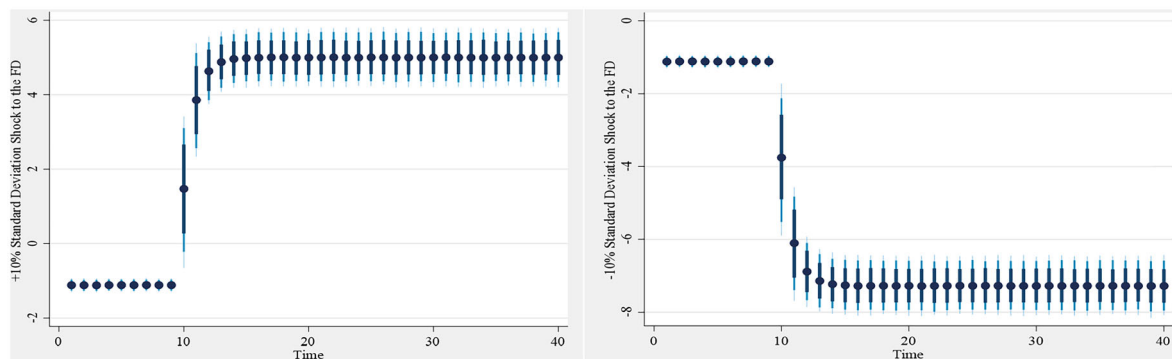
Conversely, the study provides evidence that ES has a mitigating effect on  $\ln CE$ , with the mitigating impact observed in both the short term and long term. This finding validates Hypothesis 3 ( $H_3$ ). Ghana's efforts to embrace ES yield positive outcomes, as evidenced by the finding that a 1% rise in ES leads to a 0.10% decrease in  $\ln CE$  in both the short- and long-term. The country's initiatives, such as promoting sustainability reporting, climate-resilient development, innovative waste management, green infrastructure, and renewable energy, contribute to this reduction in CE. As Ghana prioritises ES, the country will likely see further decreases in CE, aligning with its goals of mitigating climate change and promoting environmentally conscious development. In addition, the findings lend credence to the EKC hypothesis, which posits that economic growth and environmental quality are initially positively correlated but eventually become negatively correlated as economies reach a certain level of development. The results suggest that Ghana's EG is no longer accompanied by increased CE. Instead, the country's EG, driven by ES, is associated with a reduction in CE, indicating a decoupling of EG from environmental harm. In addition, this finding substantiates the empirical works of Mehmood and Kaewsaeng-on (2024b) and Zhang et al. (2022).

This study offers partial support for the EKC hypothesis in Ghana. In the early phases of FD and NR, CE increases, reflecting the initial upward slope of the EKC, driven by industrial expansion and resource extraction. This is evidenced by the long-term positive contributions of FD and NR to CE. However, a consistent negative relationship between ES and CE indicates that Ghana may be nearing the EKC



**Table 9.** Diagnostic analysis.

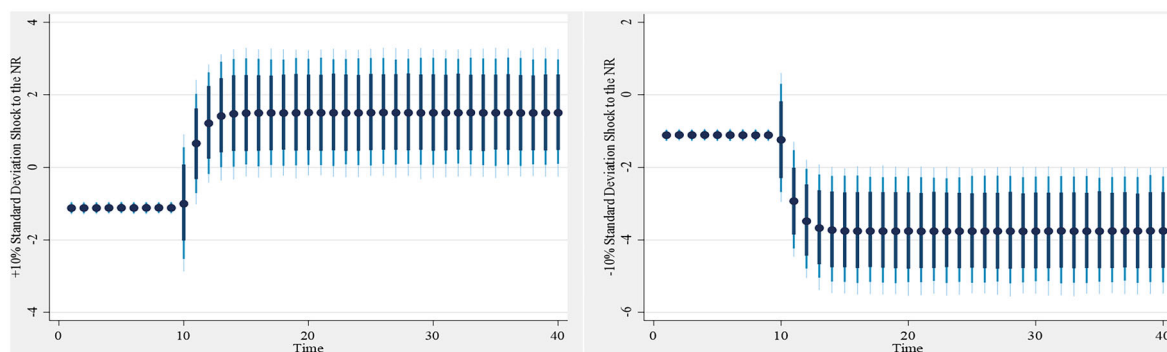
Diagnostic statistics test	Prob > $\chi^2$	Conclusion
Cameron and Trivedi's (White's) test	0.357	Homoscedastic
Breusch–Godfrey LM test	0.599	No serial correlation issue
Skewness and kurtosis tests for normality	0.704	Estimated residuals are normal

**Figure 3.** Recursive and OLS CUSUM plots of  $D. \ln CE$  with 95% confidence bands around the null.**Figure 4.** The graphs display the effect of  $\ln FD$  on  $\ln CE$  with  $\pm 10\%$  standard deviation shocks. The dark blue to light blue line denotes a confidence range of 75%, 90% and 95%. The dots signify the average forecasted value.

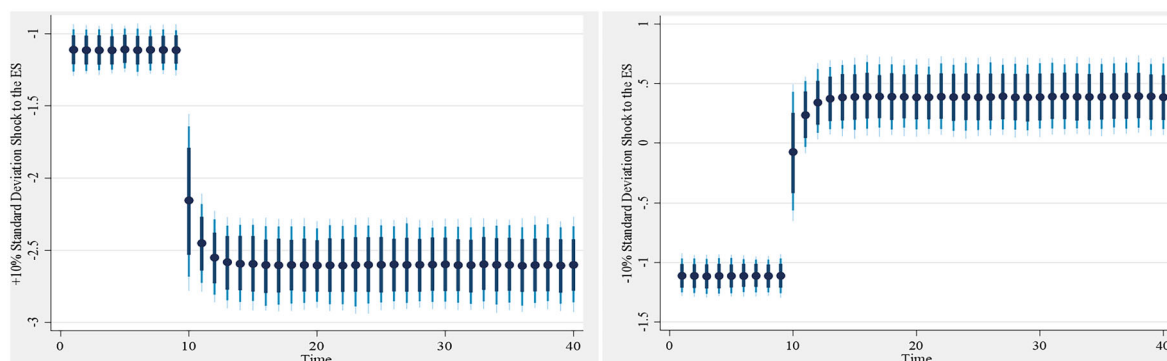
turning point. As the country adopts sustainable development practices and transitions to greener technologies and renewable energy, economic growth no longer leads to increased CE. This suggests that Ghana is progressing towards the downward slope of the EKC, balancing EG with environmental protection while developing its financial and industrial sectors.

Diagnostic tests are performed to address potential issues in DYARDL simulations, including serial correlation, heteroscedasticity, and non-normality, ensuring the validity and robustness of the results. Table 9 reports the diagnostic test results for the model, which indicate a satisfactory performance. Specifically, Cameron and Trivedi's (White's) test shows a  $p$ -value of 0.357, indicating a failure to reject the null hypothesis of homoscedasticity, which suggests that heteroscedasticity is absent. The Breusch-Godfrey LM test also yields a  $p$ -value of 0.599, confirming that no serial correlation exists in the residuals. Furthermore, the Skewness and Kurtosis tests for normality produce a  $p$ -value of 0.704, indicating that the residuals are normally distributed. In addition, the recursive and OLS CUSUM plots shown in Figure 3 demonstrate that the coefficient estimates are stable over time since the computed test statistic stays within the 95% confidence interval. These results confirm the validity and robustness of the model.

To evaluate the differential impacts of FD, NR, and ES on CE, we employed the DYARDL simulations. This involved subjecting the predictor variables to 10% positive and negative counterfactual shocks, spanning 2020–2060, the timeframe used for estimating CE. Figure 4 illustrates the effects of positive and negative variations in  $\ln FD$  on  $\ln CE$ . The results indicate that a 10% increase or decrease in  $\ln FD$  can have a discernible impact on  $\ln CE$  from the second period onwards. Moreover, the findings suggest that



**Figure 5.** The graphs display the effect of  $\ln NR$  on  $\ln CE$  with  $\pm 10$  standard deviation shocks. The dark blue to light blue line denotes a confidence range of 75%, 90% and 95%. The dots signify the average forecasted value.



**Figure 6.** The graphs display the effect of  $ES$  on  $\ln CE$  with  $\pm 10$  standard deviation shocks. The dark blue to light blue line denotes a confidence range of 75%, 90% and 95%. The dots signify the average forecasted value.

**Table 10.** Pointwise derivatives using KRLS.

LCE	Avg	SE	$t$	$P >  t $	P25	P50	P75
$\ln FD$	0.229	0.044	5.259	0.000	0.062	0.169	0.292
$\ln NR$	0.095	0.058	1.638	0.076	-0.259	0.117	0.506
$ES$	-0.080	0.011	-6.945	0.000	-0.174	-0.093	-0.003
<b>Diagnostics</b>							
Lambda	0.0796	Sigma	3	$R^2$	0.9832		
Tolerance	0.031	Eff. df	15.73	Looloss	0.8953		

a 10% positive (negative) shock to  $\ln FD$  tends to stimulate (impede)  $\ln CE$  long term. Figure 5 reveals the dynamic responses of  $\ln CE$  to positive and negative shocks in  $\ln NR$ . Notably, a 10% rise or decline in  $\ln NR$  is found to have a delayed impact on  $\ln CE$ , emerging from the second period onwards, with positive (negative) shocks leading to a long-run amplification (reduction) of  $\ln CE$ . Figure 6 depicts the response of  $\ln CE$  to 10% positive and negative shocks in  $ES$  in the context of Ghana. The results indicate that a 10% rise (drop) in  $ES$  tends to attenuate (heighten) in the short-term(long-term). The plot shows the average estimated values illustrated by dots.

Table 10 presents the pointwise derivatives of the estimated KRLS model, which demonstrates exceptional predictive accuracy in forecasting future  $\ln CE$  with a remarkably high predicting power of 0.983. The robustness of the estimates was confirmed by a thorough examination of the model at different percentiles, which showed no discernible changes in the marginal effects. The marginal impact of  $\ln FD$ ,  $\ln NR$ , and  $ES$  on  $\ln CE$  was 0.23%, 0.10%, and -0.08%, respectively. These results underscore the significance of these factors in mitigating  $CE$  in Ghana, with  $ES$  exhibiting a negative marginal effect, indicating its potential to reduce  $\ln CE$ .

Despite the findings, the question remains about how  $FD$ ,  $NR$ , and  $ES$  fluctuations will impact future  $CE$  in Ghana. To address this, we further scrutinise the long-run dynamics of  $FD$ ,  $NR$ , and  $ES$  and their

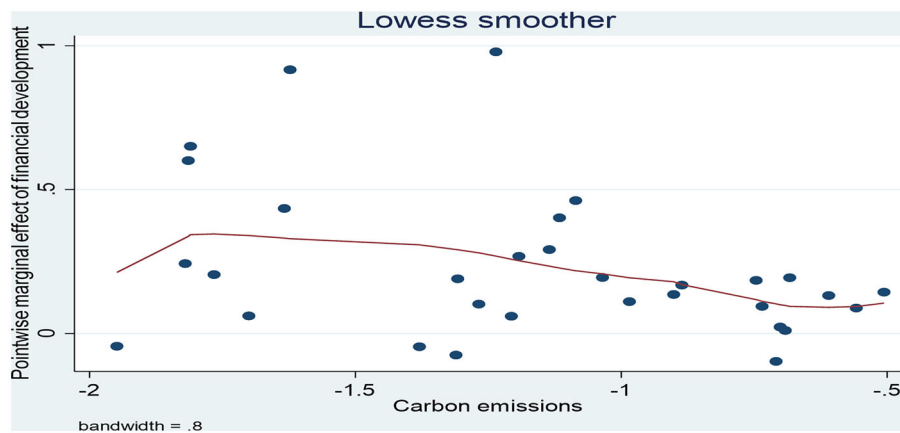


Figure 7. Pointwise marginal effect of financial development.

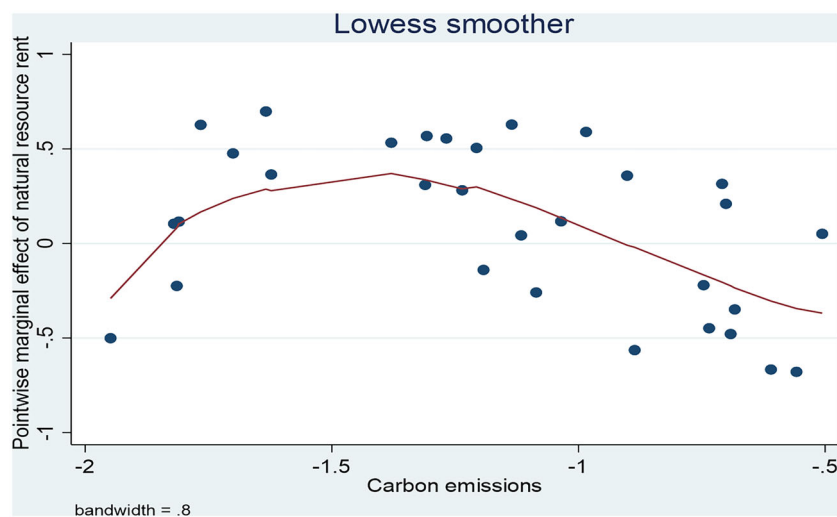
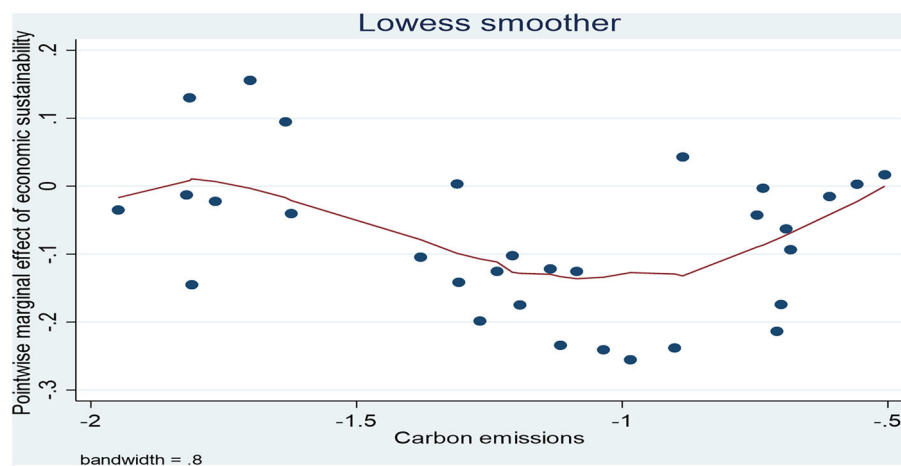


Figure 8. Pointwise marginal effect of natural resource rents.

subsequent effects on CE. Specifically, we graph the pointwise derivatives of each determinant against CE, thereby capturing the heterogeneous marginal effects. Figure 7 illustrates the association between  $\ln FD$  and  $\ln CE$ . The graphical analysis reveals an initial positive correlation, where increasing  $\ln FD$  is associated with rising  $\ln CE$  up to a threshold point. However, beyond this point, the association becomes inverse, with further increments in  $\ln FD$  leading to diminishing returns and a subsequent decline in  $\ln CE$ . This turning point may be attributed to increased efficiency, technological advancements, environmental regulations, investment in green technologies, economic restructuring, and diminishing returns. Figure 8 reveals the relationship between  $\ln NR$  and  $\ln CE$ . Initially,  $\ln NR$  falls below the baseline of  $\ln CE$ , but as it increases,  $\ln CE$  experiences a surge, exhibiting increasing returns to scale. However,  $\ln NR$  and  $\ln CE$  decline beyond a certain threshold, characterised by nearly constant marginal returns. This suggests that  $\ln NR$  may promote  $\ln CE$  up to a specific limit, but beyond that point, further improvements in  $\ln NR$  have a diminishing effect on  $\ln CE$ . The decline could represent a shift towards more sustainable practices, where economic growth becomes less dependent on natural resource exploitation. Lastly, the nexus between ES and  $\ln CE$  is depicted in Figure 9. Initially, an increase in ES leads to a marginal rise in  $\ln CE$ , indicating positive marginal returns and suggesting that ES has a beneficial effect on  $\ln CE$  up to a certain point. However, beyond this threshold, further enhancements in ES result in a pronounced decline in  $\ln CE$ , up to a specific turning point, after which the association becomes positive again. This is likely due to several factors that outweigh ES's environmental benefits, like rising consumption, new technologies, or economic expansion.



**Figure 9.** Pointwise marginal effect of economic sustainability.

## Conclusion and policy implications

The current study explored the dynamic associations between Ghana's financial development, natural resource rents, economic sustainability, and carbon emissions from 1990 to 2020. Utilizing novel econometric techniques such as Kernel Regularized Least Squares (KRLS) and the Dynamic ARDL (DYARDL) model, we investigated both the short- and long-term effects of these variables on carbon emissions. The results indicated that financial development significantly increased carbon emissions in both the short and long term. We also found that while natural resource rents had a negligible negative short-term impact on carbon emissions, they displayed a significant positive long-term effect. Additionally, economic sustainability was shown to reduce carbon emissions in both timeframes. This study's primary contribution lies in applying advanced methodological approaches to examine the interplay of financial development, natural resource rents, economic sustainability, and carbon emissions within a developing economy like Ghana. It fills a critical gap in the literature by providing empirical evidence from Sub-Saharan Africa, a region often underrepresented in global environmental and financial studies. Furthermore, the study's findings offer actionable policy recommendations emphasising the importance of green financing, sustainable resource management, and aligning policies with Ghana's Sustainable Development Goal (SDG) 13 and the Nationally Determined Contributions (NDC) under the Paris Agreement.

The findings of this study offer vital policy recommendations for the government and relevant agencies. Since financial development significantly increases carbon emissions in both the short and long term, policymakers must steer financial growth towards sustainable projects. The Bank of Ghana should implement measures that promote green financing, such as green bonds and sustainable investment funds. Drawing on Nigeria's successful Sovereign Green Bond Programme, Ghana can raise funds for renewable energy and environmental sustainability projects. To encourage participation, the government could provide tax incentives or subsidies to institutions that invest in carbon-reducing technologies, ensuring that financial growth supports ecological sustainability.

Given the negligible short-term but significant long-term positive impact of natural resource rents on carbon emissions, the government must prioritize sustainable resource management. Stricter environmental regulations should be enacted to limit the environmental degradation caused by resource extraction. Establishing a sovereign wealth fund, similar to Norway's Government Pension Fund Global, could ensure that revenues from natural resources are invested in sustainable projects, mitigating long-term environmental damage. Lastly, since economic sustainability has been found to reduce carbon emissions in both the short and long term, the government should promote policies integrating economic growth with environmental protection. Implementing carbon pricing systems and offering incentives for adopting clean energy technologies would further strengthen these efforts. Tax credits for businesses and individuals investing in renewable energy sources such as solar and wind could accelerate the transition to a low-carbon economy, ensuring economic and environmental benefits. Public awareness campaigns and sustainability frameworks such as ISO 14001 could encourage businesses and citizens to adopt greener practices.

Like any empirical study, this study has several limitations. First, the analysis is based on historical data from 1990 to 2020, which may not fully capture recent technological advances, policy shifts, or emerging economic trends that could alter the relationship between FD, NR, ES, and CE. Future research should extend the data period to include more recent developments, particularly post 2020 dynamics influenced by the COVID-19 pandemic and new energy policies. Second, while the focus on Ghana provides valuable insights into a developing country's experience, the findings may not be fully generalizable to other regions. Future studies could incorporate cross-country or regional comparisons, particularly among Sub-Saharan African nations, to determine whether the findings hold across different economic and environmental contexts. The study does not incorporate essential variables such as governance quality, industrialization, or technological innovation, which could influence carbon emissions. Future research could expand the model to include these factors, offering a more comprehensive view of the dynamics at play. Moreover, exploring nonlinear effects or threshold points in the relationships between FD, NR, ES, and CE could provide further insights, helping policymakers identify tipping points where interventions would be most effective.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Authors contributions

The article is authored by Kwadwo Boateng Prempeh, Christian Kyeremeh, Samuel Asuamah Yeboah, and Felix Danso. All authors contributed equally to the conceptualization, design, data collection, analysis, interpretation, drafting, and proofreading of the paper. All authors have agreed to take full accountability for every aspect of the work.

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## Data availability statement

Data would be made available upon reasonable request.

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