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Quest for SDG-13: The Aptness of Green Investments and Information and Communications Technology (ICT) to Emission Mitigation Among Central-African States

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ABSTRACT

The Sustainable Development Goal 13 (SDG-13) enunciates the need to combat climate change by encouraging necessary actions to reduce greenhouse gas (GHG) emissions, and this laudable goal was re-echoed at COP-28 in the UAE. Although negatively impacted by climate change, the vast literature is silent on the Central Africa (CA) region. Thus, we empirically dissect the emission-mitigating roles of green investment while integrating the moderating influences of ICT, foreign capitals (FDI), and non-renewable energy intake, within the region's economic expansion and population growth. We observe that economic expansion has a non-linear impact on emissions (an inverted U-Shaped pattern); with initial emission-inducing effects from non-renewable energy, financial development, population, and foreign capitals while green investment and ICT mitigate regional emissions. Subsequent expansion in indicators (green investments, FDI, and ICT) significantly mitigates emissions except for non-renewable energy intake. Green investments' interactive impacts with overall financial development trends also enhance regional environmental goals. Overall, the study posits that CA states can potentially mitigate environmental degradation by leveraging ICT and green investments towards the realization of SDG-13.

JEL Classification: F64, F65, Q40, Q55, O55

1 | Introduction

The need to combat climate change and reduce greenhouse gas (GHG) emissions is a global issue. While carbon dioxide (CO_2) emissions account for most GHG emissions, other gases such as methane, nitrous oxide, and fluorinated gases are more potent and have a greater impact on climate change (Yasmeen et al. 2022). GHG emissions also consider emissions from the production and transport of goods and services, thus, providing a more accurate picture of the impact of consumption on the environment (Roy 2023). Economic development presents challenges to environmental quality, including increased energy consumption, technological innovations, FDI flows, population growth, and financial development. The recent COP28 summit has highlighted the crucial role of information technology, financing, and socio-economic development in promoting clean energy sources, building climate resilience, and facilitating green and ecological climate objectives to preserve nature (Atwoli et al. 2022). In light of this, this study is particularly motivated to understand the relevance of these factors appertaining to developing countries facing significant socio-economic shocks of climate and environmental consequences in the face of limited financing and inadequate technological resources compared to developed countries.

Information communication technologies (ICTs) are identified as facilitators of renewable energy production, clean technologies, and green development, leading to a reduction in environmental poor quality (Zheng and Wang 2021). However, unless this is adequately regulated, the long-run outcome is potentially adverse. Prior examinations that have studied the relationship between ICTs and environmental quality have observed mixed results depending on the sample under investigation. For example, studies like (Chatti and Majeed 2023) observed a positive impact of technological innovation on the environment from G-7 and BRICS countries. Avom et al. (2020) studied African countries and observed that technological innovation facilitates greater economic growth which worsened environmental quality due to the lack of strict environmental regulations. Usman and Radulescu (2022) observed mixed findings for different APEC countries. They found a positive effect of patents on the environment for some developed APEC economies, but a negative impact for developing economies in the region.

Moreover, financial development (FD) and green investment's roles in environmental quality have been explored in some past studies, but the results have been mixed. Some prior studies have observed a positive link, indicating that increased FD leads to greater economic expansion and energy use, which can exacerbate the environmental poor quality, particularly in developing countries (Chen et al. 2022; Ren, Shao, and Zhong 2020). Conversely, others have found negative associations between FD and environmental deterioration (Wang et al. 2020; He, Iqbal, and Su 2023). While investigating this phenomenon from Turkey, Pata et al. (2023) found no evidence of a correlation between FD and environmental quality. Tang et al. (2023) investigated the impact of FD, trade growth, and energy use on a panel of developing Asian countries and found that FD had a negative impact on ecological, land, and carbon footprints. They also observed a moderating effect on energy consumption and environmental footprints, and FD acted as a mediator for trade expansion and environmental footprints in the selected countries.

Developing countries are increasingly contributing to the global population which may induce greater pollution. For instance, Khan et al. (2019) argue that as most transition economies grow in population, their demand increases, hence the rush for industrial systems with obsolete technologies, resulting in adverse environmental consequences. Developing countries like those in the African sub-region are important for environmental quality. The region's pollution and poor environmental quality challenges are primarily driven by fossil energy consumption and population growth agglomerations. African countries rely heavily on mining, agriculture, and forestry, which have significant negative impacts on the environment. Like many other developing countries across the continent, African countries depend on petrol, diesel, and gas and have limited domestic energy sources. Although energy prices have soared significantly in recent, they are still below market levels, as such these countries continue to rely heavily on fossil fuels. Therefore, the renewable energy generation potential of most African countries is not being adequately exploited, with hydropower, still being the primary source of renewable energy, despite the risks and potential climate issues causing water scarcity.

Over time, scholars have proven that increased consumption of fossil fuels affects environmental quality and increases pollutant emissions. Burning of fossil energy generates greenhouse gases which depletes limited natural resources. As a result, atmospheric pollution increases and contributes to climate change and global temperature rise. Conversely, renewable energy sources have been shown to alleviate environmental burdens (Ramzan et al. 2023). The transition from conventional energies to cleaner energy sources faces various barriers, including high costs associated with new infrastructure development, operating, and start-up costs (Irfan et al. 2023). Financing is required to support, fund, and manage risks, while sound financial markets are necessary to effectively allocate capital. Weak economic systems mostly invest little in industries and technological innovations required to raise energy efficiency to motivate environmental quality. Further, systemic failures such as lack of financing for green development, environmental externalities, and public social behavior hinder the achievement of quality environmental goals. Therefore, more empirical examinations like this one, are necessary to produce policy-oriented studies at the macroeconomic level on the subject matter. The call motivates this research to examine the role of financial development, economic and pollution growth, ICT development, and fossil resources, on GHG among emerging African states, particularly those in the Central African region as seen in Figure 1.

According to the World Development Indicators (2021), African countries have a low proportion of renewable energy in their energy mix. These countries also have underdeveloped financial systems and low levels of technological innovation, but they also have a low ecological footprint compared with most western counterparts. It is therefore important to note that the relationship between technological innovation, FDI, financial development, renewable energy, green investment, and environmental poor quality is complex and varies depending on the context. Some prior studies (e.g., Nguyen-Thanh, Chin, and Nguyen 2022) have found support for the pollution halo hypothesis, which suggests that developed countries with strong environmental regulations may attract FDI that leads to reduced pollution and environmental degradation. Other studies by Abid and Sekrafi (2021), however, found no support for the pollution haven hypothesis, which suggests that developing countries with lax environmental regulations may attract FDI which leads to increased pollution and environmental degradation.

This study provides the frontier examination of the region as a single bloc and the essential contributions/merits of the study draw strength from not only the robustness of analysis that produced empirical facts for an efficient policy framework but also the unique timeliness of the study in terms of the urgent need to address environmental concerns in the region. The countries in the region face significant environmental poor-quality challenges. Central Africa has become one of the most susceptible

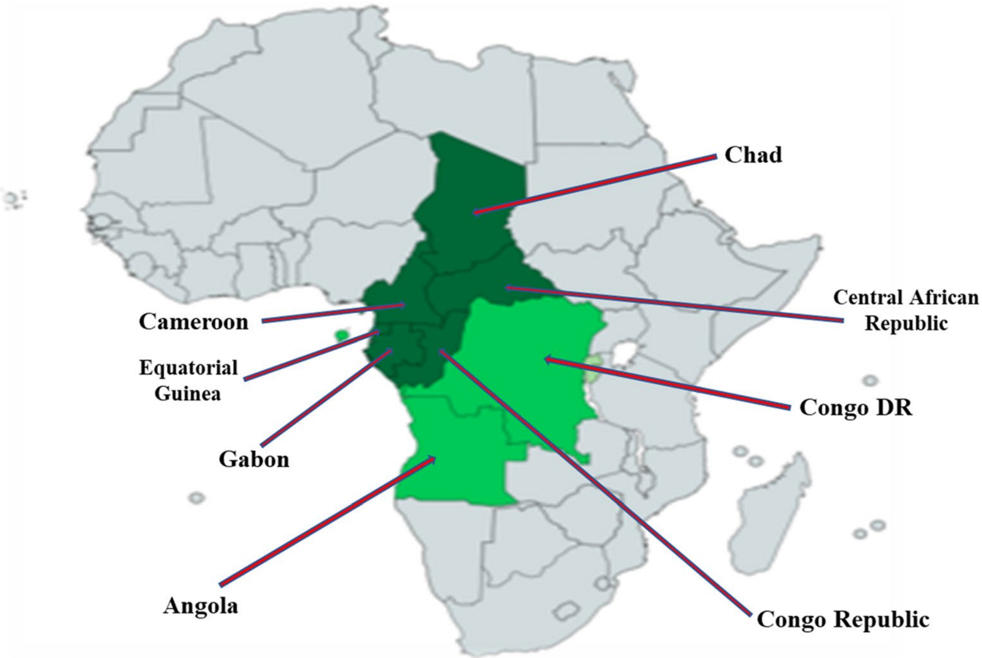

FIGURE 1 | A map of Africa indicating the Central African Region. (*Source:* Authors' design).

regions globally to environmental and climate-related disturbances. Central African countries are already experiencing the consequences of unpredictable weather changes and droughts that displace people, hinder governance, and incite tensions at all societal levels. According to the global ND-GAIN index, all Central African countries receive low scores below 0.55. The area's vulnerability is attributed to several factors, including political and economic grievances, fragile state institutions, rapid population growth, a long history of violent conflict, low financial development, and widespread displacement. Climate events, combined with these trends, are a cause of significant concern. Extreme weather and droughts have worsened the already vulnerable situation in some Central African countries. In the Central African Republic (CAR), the scarcity of natural resources like water and cattle grazing land has exacerbated competition for land and fueled intercommunal tensions and conflicts between herders and farmers. In Chad and the Democratic Republic of Congo, climate shocks have worsened food crises as agricultural production already reels from the effects of violence and insecurity. While such dynamics also occur in other parts of the continent, Central Africa's protracted crises and unique set of risk factors make its citizens and countries particularly vulnerable to climate shocks. Hence given the quest for SDG-13 attainment, this study presents a robust analysis within the environmental context of the region based on the proposition that the relationship between technological innovation, green investment, FDI, financial development, and greenhouse gas-related environmental issues may not be straightforward in this bloc.

The study contributes to the literature in three different ways: First, unlike previous studies that have focused primarily on developed nations or broader groups of emerging economies (such as Chatti and Majeed 2023, who examined G-7 and BRICS countries), this study specifically investigates the complex dynamics of greenhouse gas emissions in Central African nations, a region often overlooked in environmental research. Second, while prior research has shown mixed results regarding the impact of financial development on environmental quality (e.g., Chen et al. 2022; Wang et al. 2020), this study provides novel insights into the non-linear impacts of various factors, including the inverted U-shaped relationship between economic growth and ecological emissions in the Central African context. Second, while earlier works have examined individual factors in isolation, such as the impact of technological innovation on environmental quality (Avom et al. 2020; Usman and Radulescu 2022), this study takes a more comprehensive approach by simultaneously analyzing the roles of financial development, green finance, foreign direct investment, non-renewable energy consumption, and ICT development. Finally, in contrast to studies that have found mixed or inconclusive results regarding the relationship between financial development and environmental quality (e.g., Pata et al. 2023, who found no correlation in Turkey), this study provides novel insights into the non-linear impacts of various factors, including the inverted U-shaped relationship between economic growth and ecological emissions in the Central African context while demonstrating the potential for green finance and ICT to mitigate pollution. This study offers a more detailed and regionally relevant understanding of emission mitigation strategies, thereby addressing a significant gap in the existing literature.

2 | Literature Review

2.1 | Green Investment and Environmental Quality

Green investment is an innovative financial strategy that seeks to advance the cause of environmental conservation and foster sustainable economic and social progress. The approach entails the prioritization of clean institutions and environmental protection by financial institutions and governments through diverse financial instruments, including loans, equity, and bonds, among others, aimed at mitigating the underinvestment in environmental protection.

In recent years, a growing body of literature has focused on the concept of green investment and its associated policies (Huang and Chen 2022). These studies primarily aim to conceptualize green investment and green credit policies. For instance, green investment can enhance efficiency and environmental quality by directing funds away from high-pollution industries and towards environmentally friendly sectors (Nenavath 2022; Ren, Shao, and Zhong 2020). It also emphasizes the importance of investing in green financial capital and ecological control to minimize the adverse impacts of environmental deterioration (Kirikkaleli and Adebayo 2022).

The Environmental Kuznets Curve (EKC) structure posits that the influence of green investment on environmental pollution can be classified into three distinct categories, namely scale, structural, and technical. This assertion is corroborated by several scholars. Tang et al. (2022) posited that financial development may exert an influence on regional trade, thereby inducing alterations in local production frameworks and ultimately impacting the environment. Meo and Abd Karim (2022) discovered that the presence of financial constraints may impede endeavors to mitigate air pollution. Green investment has the potential to offer financial support to businesses, enabling them to alter their production scale and ultimately decrease their environmental impact. Zheng et al. (2022) found that the implementation of green loan policies has a positive effect on pollution abatement by both state-owned and private-owned firms. By developing a green investment index using a common weight DEA composite indicator, they demonstrated that green investment could reduce environmental pollutant emissions (Iqbal et al. 2021).

2.2 | Financial Development, FDI, and Environmental Quality

According to Torras and Boyce (1998), financial development-environment nexus is dynamic and changes over time. The EKC curve, which describes the relationship between development and environmental welfare, suggests that in the early stages of development, countries prioritize policies that promote economic growth over environmental conservation. However, as economies stabilize, attention begins to shift towards natural resource conservation and sustainable development, resulting in a U-shaped curve that describes the relationship between income and the environment (Onifade 2022). Initially, environmental degradation may occur rapidly as adopting green policies may be too expensive for developing countries to justify. However, as concerns about the quality of air and water increase, economies begin to seek out environmentally friendly solutions. Fakher et al. (2022) discovered that economic and financial development contributes to environmental degradation (specifically carbon emissions) initially, but over time, this deterioration slows down and even improves in some cases. Similarly, Shahbaz found a non-linear relationship between financial development and environmental degradation (specifically energy consumption and carbon dioxide emissions) across countries with different income levels. While the effects of technological innovations and FDI on renewable and non-renewable energy may vary, it is widely accepted that financial development is a critical factor in determining the success of the renewable energy sector. Jianguo et al. (2022) have observed that the growth of the renewable energy industry may be impeded by an inadequately developed financial system. Conversely, Usman, Jahanger, et al. (2022) have reported that a well-established financial system can effectively facilitate the development of renewable energy industries. Nonetheless, the existing body of literature regarding this subject matter is restricted, and the results are ambiguous. Usman, Kousar, et al. (2022) discovered that financial development and trade openness had a significant positive influence on renewable energy consumption. Conversely, Dada et al. (2022) observed that finance played a favorable role in China's renewable energy sector, but also noted adverse effects stemming from foreign direct investment, trade openness, and energy consumption. Jianguo et al. (2022) have identified income, CO_2 emissions, and oil prices as key supportive forces for raising the consumption of renewable energy in the OECD bloc.

Upon conducting a comprehensive analysis of empirical literature, it has been determined that the effects of technological advancements, foreign direct investment, and financial activities on the environment have been extensively researched. However, the extent of their involvement in both renewable and non-renewable energy remains inadequately researched, and the outcomes obtained thus far are inconclusive. Further research is necessary to address the discourse surrounding technological advancements, foreign direct investment, and financial considerations in relation to both renewable and non-renewable energy sources. Significantly, as far as our understanding goes, there is a lack of research that discloses and compares the outcomes of countries involved in Central Africa. The present study endeavors to furnish substantial policy recommendations in accordance with the aforementioned objectives.

2.3 | ICT, GDP, and Environmental Quality

The use of computing technologies has become a topic of interest for scholars studying energy issues. However, the fast expansion of these technologies could potentially increase energy needs, posing a challenge to achieving sustainable development goals. While using information and communication technology (ICT) can promote economic growth and energy efficiency, it may also lead to an increase in the use of non-renewable energy sources (Shehzad et al. 2022). The impact of ICT on energy consumption and environmental quality varies among different countries due to heterogeneity in institutional quality, development status, and geographical location.

Studies have suggested that ICT can reduce carbon emissions and improve energy efficiency by replacing traditional technology with less energy-intensive products (Chatti and Majeed 2023). However, the effect of ICT on energy consumption and pollutant emissions is not straightforward and depends on the country's dominant element. For example, studies have shown that ICT contributes to electricity consumption and carbon emissions in

N-11 countries but has a reduction effect on carbon emissions in high and middle-income countries.

Despite the mixed findings, it is generally agreed that the adoption of ICT can help improve ICT equipment efficiency and address environmental issues through the use of environmentally friendly project applications. By combining the use of clean energy sources with the adoption of ICT, energy consumption and carbon emissions can be reduced (Dogan and Pata 2022). However, it is important to consider the heterogeneity among countries when analyzing the impact of ICT on energy consumption and carbon emissions.

In line with the above, it is evident that there are divergent opinions regarding ICT's effect on energy consumption as well as the environment. One perspective is that ICT can save energy and reduce carbon emissions. For instance, Ma et al. (2022) found that the reduction effect of ICT on carbon emissions is significant after surpassing a threshold, and Weimin et al. (2022) observed an inverted "U-shaped" relationship between ICT and carbon emissions in 142 countries. Additionally, ICT can enhance energy efficiency and support environmentally-friendly projects to lower energy use and foster a corresponding decline in emissions (Manzoor et al. 2022).

However, the second viewpoint contends that ICT's use increases pollution emissions. Chatti (2021) reported that ICT and economic growth contribute to electricity consumption in the short and long run. Studies by Usman et al. (2021), and Liu et al. (2021), demonstrate a positive relationship between ICT and carbon emissions in different countries. Nevertheless, Liu et al. (2021) presented a different perspective on the impact of ICT on carbon emissions, stating that its reduction effect varies depending on income level, whereby it heightens emissions in nations with low income but lowers the same in high/middle-income nations.

Economic influence can be categorized into three types: scale, structural, and technical (Kirikkaleli, Abbasi, and Oyebanji 2023). Firstly, through scale effects, economic development causes increased pollution due to greater consumption of natural resources and energy at a certain level of technology (Gan, Yang, and Liang 2021). However, economic expansion can also lead to higher living standards and greater investment in eco-friendly products. Furthermore, people with higher incomes tend to demand stricter environmental standards, which can motivate governments to enforce more effective measures to reduce pollution. Secondly, through structural effects, the shift from labor-intensive to service-oriented industries that accompany economic growth tends to reduce environmental pollutants. Highly developed economies tend to have a less polluting industrial structure. However, the structural effect of an open economy can be influenced by foreign investors and trade (Sharma, Kautish, and Uddin 2020). Foreign Direct Investment (FDI) may negatively impact host countries' environment through structural effects. Finally, through technical effects, people's awareness and demand for environmental protection increases with economic growth, which drives governments to develop stronger environmental management policies and gradually improve the quality of the environment.

Studies have revealed that in an open global economy, developing countries could potentially become "pollution havens" (Liu et al. 2021; Huang and Chen 2022). This is because developed nations generally impose stricter environmental regulations and higher taxes on environmental pollution, whereas developing nations typically have lower taxes. As a result, corporations may consider the lower emission costs when selecting locations.

In addition, economic growth can impact environmental pollution through technological factors. People have become more aware of environmental issues, leading to an increased demand for environmental protection. Moreover, the government's determination and financial resources to manage the environment have also grown with economic growth, resulting in an overall improvement in environmental quality.

2.4 | Literature Gaps

In line with the above discussed, it is observed that the body of extant research has broadly provided valuable insights into the relationship between technological innovations, economic growth, financial development, and carbon emissions. However, there is a lack of studies that specifically examine this relationship in specific African contexts, like central African countries. One critical gap in existing research is the oversight of the role of information and communication technology (ICT) in moderating and influencing the non-linear effects of financial development agents like FDI and green investment on greenhouse gas emissions. Furthermore, conducting a heterogenous analysis that takes into account factors such as economic expansion and population growth may aid in developing tailored strategies for low-greenhouse gas emission contexts by strengthening the financial systems of central African countries.

3 | Methodology

3.1 | Data Source

Data from five Central African nations (namely, Angola, Cameroon, Republic Congo, Democratic Republic of Congo, and Gabon) over the period 1996 to 2019 was used for the analysis and there corresponding description and measurement units have been provided in Table 1. Chad and the Central African Republic were not included in the sample because of data constraints. The study period was selected based on data availability. Specifically, data on greenhouse gas (GHG) emissions for all the studied countries was available to 2019 as of the time the analysis was conducted. Also, for countries like Gabon and Cameroon, data on the indicators of financial development was available until 2019. Given that data on GHG emissions, broad money growth, broad money, domestic credit to private sector by banks, foreign direct investment, gross domestic product (GDP), individuals using the internet, mobile cellular subscriptions, and renewable energy for most periods below 1996 was not available for some of the countries, authors settled on 1996–2019 because significant data on the series could be obtained within that period. All missing data within the time frame was filled via the data interpolation and extrapolation technique.

TABLE 1 | Data description and measurement units.

The indicators	Given signs	Their measurement	The source	References
Greenhouse gas emissions	GHG	Kt of CO_2 equivalent	WDI	Tariq et al. (2022), Aquilas and Atemnkeng (2022)
Population growth	POP	Annual percentage	WDI	You, Li, and Waqas (2024)
Green investment	GF	Consumption of Renewable energy taken as % of total final energy use	WDI	Wu et al. (2021), Nawaz et al. (2021)
Foreign direct investment	FDI	The net inflows (% of GDP)	WDI	Wang, Li, and Li (2024)
Nonrenewable energy	NRE	Fossil fuels (% of total)	WDI	Jinapor, Suleman, and Cromwell (2023), Onifade, Gyamfi, Alola, et al. (2023)
Gross domestic product	GDP	GDP per capita (constant 2015 US $)	WDI	Barak et al. (2024)
Financial development (FD)				
Broad money	BM	(%) of GDP	WDI	Qayyum et al. (2021)
Domestic credit to private sector by banks	DCB	(%) of GDP	WDI	Prempeh (2024), Onifade, Gyamfi, Haouas, et al. (2023)
Broad money growth	BMG	Yearly (%)	WDI	Hung (2022)
Information and communication technology (ICT)				
Individuals using the internet	INT	Percentage (%) of population	WDI	Jakada et al. (2023)
Mobile cellular subscriptions	MCS	Per 100 people	WDI	Gyamfi, Onifade, and Ofori (2023)
Fixed telephone subscriptions	FTS	Per 100 people	WDI	Ebaidalla and Abusin (2022)

In prior investigations by Boamah et al. (2023), and Duan et al. (2023), environmental quality (EQ) was proxied by only CO_2 emissions. However, emissions of CO_2 are not the only constituent of greenhouse gas (GHG) emissions as nitrous oxide (N_2O) emissions, methane (CH_4) emissions, sulfur dioxide (SO_2) emissions, and PM25 also play a key role. Therefore, following Tariq et al. (2022) and Aquilas and Atemnkeng (2022), we used GHG emissions as our measure of EQ. Besides, we used renewable energy consumption (REC) to measure green investment (GF) in line with the studies of Wu et al. (2021) and Nawaz et al. (2021). This variable was used because it has proven to be environmentally friendly in both developed and developing economies. For instance, Triki et al. (2023) investigation on Saudi Arabia confirmed REC as gainful to environmental sustainability. Moreover, we proxied nonrenewable energy (NRE) by fossil fuels in line with the studies of Jinapor, Suleman, and Cromwell (2023) and Onifade, Gyamfi, Alola, et al. (2023). This variable was considered over others because it is consumed in every economy, and has been widely proven to be environmentally harmful (Roy 2023). The data on GHG, REC, fossil fuels, population growth (POP), economic growth (GDP), and foreign direct investment (FDI) was directly accessible from the World Bank. Meanwhile, the PCA approach was used to construct indexes for financial development (FD), and information and communication technology (ICT). The index for FD was constructed using the private sector's domestic credit obtained from banks, the broad money, as well as its growth. These variables were considered because they capture the efficiency, access, stability, and depth of financial systems. On the other hand, individuals using the internet, the number of subscriptions to mobile cellular, as well as fixed telephone subscriptions were utilized to compute the index for ICT in line with the study of Ebaidalla and Abusin (2022). As displayed in Tables 2 and 3, the first two components respectively accounted for 83% and 91% of the variances in the estimated indexes. Also, the corresponding eigen values of the components were greater than 1 indicating that, they were very substantial. Because the third component had very low explanatory powers, they could not be included in the index computations. Following Hung (2022), the indexes were computed as a linear combination of the series involved. The

TABLE 2 | Creating PCA for financial development.

The component	The eigenvalue	The difference	The proportion	Cumulative
Comp1	1.41	0.34	0.47	0.47
Comp2	1.07	0.55	0.36	0.83
Comp3	0.52	—	0.17	1.00

Eigenvectors (loadings)			
Variable	**Comp1**	**Comp2**	**Comp3**
Private sector's credits (domestic) from banks	0.68	0.43	0.75
The broad money	0.61	0.52	0.58
The growth in Broad money	−0.41	0.74	0.32

TABLE 3 | PCA for information and communication technology.

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	1.57	0.41	0.52	0.52
Comp2	1.16	0.89	0.39	0.91
Comp3	0.27	—	0.09	1.00

Eigenvectors (loadings)			
Variable	**Comp1**	**Comp2**	**Comp3**
Individuals using the internet	0.36	0.95	0.13
Mobile cellular subscriptions	0.67	−0.20	−0.74
Fixed telephone subscriptions	−0.65	0.24	0.66

concerned variables were chosen taking into consideration the sustainable development goals (SDGs) of the United Nations.

3.2 | Model Construction and Theoretical Underpinning

The role of green investment (GF), foreign direct investment (FDI), non-renewable energy (NRE), and financial development (FD) in meeting the emission targets of the Paris (2015) agreement cannot be underrated. In order to determine whether the variables contribute to the motives of the above accord or not, an exploration on the nexus between GF, FDI, NRE and environmental quality (EQ), accounting for the moderating role of FD in the context of Central Africa was deemed appropriate. To accomplish this goal, the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) framework of Dietz and Rosa (1997) was engaged for the analysis. This model builds on Ehrlich and Holdren's (1971) IPAT theoretical framework which was developed to explain environmental issues triggered by human activities in the early 1970s. According to the framework, ecological impacts are products of the size of population, income and technology of the human population in question. The IPAT model is expressed as;

$$I = P \times A \times T \tag{1}$$

where I denotes environmental impacts caused by population size (P), affluence (A) and technology (T). The IPAT framework is intriguing because it gives such an intuitive narrative, and is exquisite in its simplicity. However, intuitive narratives are not always the best solution to complex issues. Also, Dietz and Rosa (1994) contend that, the model is a simple mathematical equation, and assumes exact proportionality among the variables. As such, it is not the best choice for testing hypothesis. According to York, Rosa, and Dietz (2003), the IPAT framework allows the drivers of ecological change and their effects to be fully analyzed. However, it fails to account for the non-monotonic impacts of the driving forces. To remedy the above shortcomings, a stochastic version of the IPAT framework termed STIRPAT, was developed by Dietz and Rosa (1997). This model provides the opportunity to empirically test various hypothesis rather than a mere equation (York, Rosa, and Dietz 2003). The STIRPAT model is expressed as;

$$I_{it} = a_i P_{it}^{\beta_1} A_{it}^{\beta_2} T_{it}^{\beta_3} \mu_{it} \tag{2}$$

where β_1, β_2, and β_3 are the exponents of P, A, and T correspondingly, a is the constant term, i is the cross-sectional units, t is the study period and μ is the random error term which is assumed to be normally distributed with a mean of zero and a variance of σ^2. Rewriting the above model in a logarithmic form, the following model was obtained;

$$\ln I_{it} = a_i + \beta_1 \ln P_{it} + \beta_2 \ln A_{it} + \beta_3 \ln T_{it} + \mu_{it} \tag{3}$$

where I represents environmental impacts proxied by greenhouse gas (GHG) emissions, P denotes population surrogated by population growth (POP), A is affluence proxied by GDP, and T represents technology, which is represented by ICT. Moreover, a_i is the constant term, while i, t, and μ epitomize the investigated countries, timeframe and error term respectively. A unique feature of the STIRPAT framework is that, it permits the inclusion of additional variables needed in a study (Habiba, Xinbang, and Anwar 2022; Dietz, Rosa, and York 2007). We therefore augmented Equation (3) with GF, FDI, NRE, and FD to obtain the baseline model (hereafter Model A) of the study as;

$$\begin{aligned}\ln\text{GHG}_{it} = a_i + \beta_1 \ln\text{POP}_{it} + \beta_2 \ln\text{GDP}_{it} + \beta_3 \ln\text{GF}_{it} \\ + \beta_4 \ln\text{FDI}_{it} + \beta_5 \ln\text{NRE}_{it} + \beta_6 \ln\text{ICT}_{it} \\ + \beta_7 \ln\text{FD}_{it} + \mu_{it}\end{aligned} \quad (4)$$

where $\beta_1, \ldots, \beta_7$ denote the elasticities lnPOP, lnGDP, lnGF, lnFDI, lnNRE, lnICT, and lnFD correspondingly. Theoretically, Besides, polluting fuels continue to be the major source of energy for people in economies (Voumik et al. 2022). So as the rate of population increases, so will be the demand for these energies to drive daily activities, which end up polluting the environment (Voumik, Sultana, and Dey 2023). However, when the populace become aware of the consequential effects of polluting energies and decide to embrace clean energies in their daily routines, ecological quality will be enhanced. Based on this premise, we project the coefficient of POP to be either positive $\left(\beta_1 = \frac{\partial \ln\text{GHG}_{it}}{\partial \ln\text{POP}_{it}} > 0\right)$ or negative $\left(\beta_1 = \frac{\partial \ln\text{GHG}_{it}}{\partial \ln\text{POP}_{it}} < 0\right)$ aligning with the study of Liddle (2014). Moreover, there is no clear association between GDP and ecological pollution because the level of pollution in economies is influenced by factors like technology, population size, agriculture, deforestation, industrialization, and energy utilization amongst others. According to Li et al. (2023); Li, Zhang, and Zhu (2023), economic viability and pollutant emissions are positively linked because both advanced and emerging economies tend to strive for higher economic development, dominated by pollution driven activities. Also, the surge in urbanization fuels rapid economic expansion, which in turn increases energy utilization, and subsequently, more ecological pollution. In the above scenarios, the scale effect tends to be higher than the technique effect of economic development. However, when the technique effect surpasses the scale effect, economic progress advances ecological sustainability via pollution mitigation. Since the economic advancement-ecological pollution link is inconclusive, we expect the elasticity of GDP to be either positive $\left(\beta_2 = \frac{\partial \ln\text{GHG}_{it}}{\partial \ln\text{GDP}_{it}} > 0\right)$ or negative $\left(\beta_2 = \frac{\partial \ln\text{GHG}_{it}}{\partial \ln\text{GDP}_{it}} < 0\right)$ as seen in the cases of Kirikkaleli et al. (2023) and Kasperowicz (2015) correspondingly. Furthermore, GF plays a crucial role in promoting ecological sustainability. To begin with, GF stimulates investments in green energy generation and utilization. It also promotes investments in green technological innovations, energy efficiency, and research and development activities that enhance ecological safety. Microeconomically, GF promotes green innovation among businesses, lowers the cost of market transactions, and directs consumers toward green consumption (Wang, Pan, and Zhang 2016). According to Xie, Wang, and Cong (2020); Xie, Ouyang, and Choi (2020), GF acts as a twofold catalyst for improved ecological growth. On one hand, GF offers financial support to firms that work to protect the environment. This lowers the financial obstacles that the firms face in advancing ecological quality. On the other hand, GF excludes from the market, businesses with excessive energy consumption and pollution rates. This promotes ecological and economic progress by increasing the effectiveness of capital utilization. Additionally, GF offers support for environmental preservation and green industry initiatives to help promote rural revitalization and ecological safety (Wang and Zheng 2019). Based on these grounds, we expect the coefficient of GF to be negative $\left(\beta_3 = \frac{\partial \ln\text{GHG}_{it}}{\partial \ln\text{GF}_{it}} < 0\right)$, aligning the study of Sampene et al. (2022). Besides, FDI influences the environment in two diverse ways. First, advanced countries via the channel of FDI damages the ecosystem of developing nations by transferring high-polluting production activities to those countries due to their weak ecological standards. This connection between FDI and ecological pollution is termed pollution haven hypothesis (PHH) (Boamah et al. 2023). In contrast, some foreign entities invest more in research and development activities that help to advance ecological sustainability in host countries. Some foreign establishments also embrace green energy, energy efficiency, and eco-innovative technologies in their undertakings. This help to transition the industrial structure from high-pollution intensive to low-pollution intensive, thereby stimulating ecological quality. This association between FDI and ecological distress is known as pollution halo hypothesis (PHA) (Yilanci et al. 2023). Because FDI is related to ecological pollution in diverse ways, we project its elasticity to be either positive $\left(\beta_4 = \frac{\partial \ln\text{GHG}_{it}}{\partial \ln\text{FDI}_{it}} > 0\right)$ or negative $\left(\beta_4 = \frac{\partial \ln\text{GHG}_{it}}{\partial \ln\text{FDI}_{it}} < 0\right)$. Moreover, polluting energies drive activities like industrialization; agriculture, natural resource extraction; and infrastructure amongst others. So, the more these activities are undertaken in economies, the more energies from dirty sources are consumed, thereby surging the rate of pollution. This point aligns the assertion of Udeagha and Ngepah (2022) that, emissions from carbon are linked to the utilization of energy. Since the energy mix of Central Africa is dominated by polluting energies, we expect the coefficient of NRE to be positive $\left(\beta_5 = \frac{\partial \ln\text{GHG}_{it}}{\partial \ln\text{NRE}_{it}} > 0\right)$. Also, Tamazian, Chousa, and Vadlamannati's (2009) study revealed that FD plays a significant role in promoting or impeding environmental improvement. According to Tamazian and Bhaskara Rao (2010), development in the financial sector hasten the adoption of improved environmental practices thereby boosting ecological quality. For instance, FD enables firms and economies to invest in energy-efficient and eco-innovative activities that help to improve ecological sustainability. Also, robust financial systems attract foreign investments that help to advance ecological sustainability. According to Polat (2021), foreign investment is the most efficient channel through which green innovations could be transferred from one jurisdiction to the other. This reinforces the beneficial association between FD and ecological quality. Contrastingly, studies by Ju et al. (2023) and Tong, Ortiz, and Wang (2023) described FD as an agent of ecological contamination. Sadorsky (2010) also viewed financial sector advancement as a major factor that reduces ecological safety. The wealth effect was cited by the author to back the above claim. According to this assumption, rising wealth leads to rising economic activities. But the more economic activities are undertaken, the more fossil fuel energy sources are consumed, resulting in more environmental damage. Besides, consumers can easily access funds from financial markets to purchase goods like refrigerators and cars among others. These goods increase the rate of energy utilization resulting in pollutant emissions. Also, well-developed financial systems make it easy for businesses to access capital to acquire equipment and other assets to expand their production. The rise in production leads to the rise in energy utilization, which end up polluting the environment. Based on these mixed results, we predict the coefficient of FD to be either positive $\left(\beta_6 = \frac{\partial \ln GHG_{it}}{\partial \ln FD_{it}} > 0\right)$ or negative $\left(\beta_6 = \frac{\partial \ln GHG_{it}}{\partial \ln FD_{it}} < 0\right)$. Moreover, Jiang et al. (2020) discovered a positive association between FD and GF in 25 Chinese provinces. Nkoa's (2018) study on 52 African nations affirmed FD as a major factor that influenced foreign investments. In the study of Ma and Fu (2020), FD raised the rate of energy utilization in 120 global economies. Developments in the financial sector can also significantly explain the perfomance of the ICT sector. Since FD has a link with GF, FDI, NRE, and ICT, its interaction with the series might have an influence on ecological sustainability. To test the validity of this assumption in Central Africa, the interactive terms between FD and GF (FD×GF), FD and FDI (FD×FDI), FD and NRE (FD×NRE), and FD and ICT (FD×ICT), are incorporated into the baseline framework resulting in our second estimated model (hereafter Model B) as;

$$\begin{aligned}\ln GHG_{it} = {} & a_i + \beta_1 \ln POP_{it} + \beta_2 \ln GDP_{it} + \beta_3 \ln GF_{it} \\ & + \beta_4 \ln FDI_{it} + \beta_5 \ln NRE_{it} + \beta_6 \ln ICT_{it} \\ & + \beta_7 \ln FD_{it} + \delta_1 \left(\ln FD_{it} \times \ln GF_{it}\right) \\ & + \delta_2 \left(\ln FD_{it} \times \ln FDI_{it}\right) + \delta_3 \left(\ln FD_{it} \times \ln NRE_{it}\right) \\ & + \delta_4 \left(\ln FD_{it} \times \ln ICT_{it}\right) + \mu_{it}\end{aligned} \tag{5}$$

where $\delta_1, \delta_2, \delta_3$, and δ_4 are the coefficients of interactive terms (FD×GF), (FD×FDI), (FD×NRE), and (FD×ICT), correspondingly. In Equation (5), the partial differentiation of GHG with respect to FD are expressed as;

$$\frac{\partial \ln GHG_{it}}{\partial \ln FD_{it}} = \beta_7 + \delta_1 \ln GF_{it} \tag{5a}$$

$$\frac{\partial \ln GHG_{it}}{\partial \ln FD_{it}} = \beta_7 + \delta_2 \ln FDI_{it} \tag{5b}$$

$$\frac{\partial \ln GHG_{it}}{\partial \ln FD_{it}} = \beta_7 + \delta_3 \ln NRE_{it} \tag{5c}$$

$$\frac{\partial \ln GHG_{it}}{\partial \ln FD_{it}} = \beta_7 + \delta_4 \ln ICT_{it} \tag{5d}$$

More attention would be accorded to the parameter relevance (e.g., β_7 and δ_1). A positive marginal effect $\left(\beta_7 + \delta_1 \ln GF_{it}\right)$ implies, increased GF and FD results in increased ecological pollution, while a negative marginal effect signposts that, increased GF and FD results in decreased environmental contamination. To ascertain whether GF, FDI, NRE, and ICT are nonlinearly related to EQ or not, the baseline model is augmented with the square terms of GF, FDI, NRE, and ICT resulting in our third estimated model (hereafter Model C) as;

$$\begin{aligned}\ln GHG_{it} = {} & a_i + \beta_1 \ln POP_{it} + \beta_2 \ln GDP_{it} + \beta_3 \ln GF_{it} \\ & + \beta_4 \ln FDI_{it} + \beta_5 \ln NRE_{it} + \beta_6 \ln ICT_{it} \\ & + \beta_7 \ln FD_{it} + \varphi_1 \ln GF^2{}_{it} + \varphi_2 \ln FDI^2{}_{it} \\ & + \varphi_3 \ln NRE^2{}_{it} + \varphi_4 \ln ICT^2{}_{it} + \mu_{it}\end{aligned} \tag{6}$$

where φ_1, φ_2, and φ_3 are the coefficients of square terms GF^2, FDI^2, and NRE^2 respectively. For a nonlinear relationship to be validated, the parameters of the series and their square terms must be significantly different. A U-shaped association is validated if β_3, β_4, β_5, and β_6 are negative (β_3, $\beta_4, \beta_5, \beta_6 < 0$) while $\varphi_1, \varphi_2, \varphi_3$, and φ_4 are positive ($\varphi_1, \varphi_2, \varphi_3, \varphi_4 > 0$). In contrast, the relationship is inverted U-shaped β_3, β_4, β_5, and β_6 are positive (β_3, $\beta_4, \beta_5, \beta_6 > 0$) while $\varphi_1, \varphi_2, \varphi_3$, and φ_4 are negative ($\varphi_1, \varphi_2, \varphi_3, \varphi_4 < 0$). Differentiating GHG with respect to GF, FDI, NRE, and ICT in Equation (6) gives rise to the following threshold specifications;

$$\frac{\partial \ln GHG_{it}}{\partial \ln GF_{it}} = \beta_3 + 2\varphi_1 \ln GF_{it} \tag{6a}$$

$$\frac{\partial \ln GHG_{it}}{\partial \ln FDI_{it}} = \beta_4 + 2\varphi_2 \ln FDI_{it} \tag{6b}$$

$$\frac{\partial \ln GHG_{it}}{\partial \ln NRE_{it}} = \beta_5 + 2\varphi_3 \ln NRE_{it} \tag{6c}$$

$$\frac{\partial \ln GHG_{it}}{\partial \ln ICT_{it}} = \beta_6 + 2\varphi_4 \ln ICT_{it} \tag{6d}$$

Setting Equation (6a–6d) to zero, the turning points of the variables can be computed as;

$$\ln GFI_{it} = \frac{-\beta_3}{2\varphi_1} \tag{6e}$$

$$\ln FDI_{it} = \frac{-\beta_4}{2\varphi_2} \tag{6f}$$

$$\ln NRE_{it} = \frac{-\beta_5}{2\varphi_3} \tag{6g}$$

$$\ln ICT_{it} = \frac{-\beta_6}{2\varphi_4} \tag{6h}$$

To finally integrate the EKC assessment for the region, the baseline model is augmented with (GDP^2) thus resulting in our fourth estimated model (hereafter Model D) as;

$$\begin{aligned}\ln GHG_{it} = {} & a_i + \beta_1 \ln POP_{it} + \beta_2 \ln GDP_{it} + \beta_3 \ln GF_{it} \\ & + \beta_4 \ln FDI_{it} + \beta_5 \ln NRE_{it} + \beta_6 \ln ICT_{it} \\ & + \beta_7 \ln FD_{it} + \pi \ln GDP^2{}_{it} + \mu_{it}\end{aligned} \tag{7}$$

where π is the coefficient of GDP^2. The EKC hypothesis posits that ecological pollution increases with income at the initial stages of economic progress. But after attaining some threshold levels, any additional income growth would aid ecological safety. The hypothesis proposes an inverted U-shaped association between income and environmental deterioration. Before the EKC assumption could be validated, the coefficients of income and income square must be different and statistically significant. The interpretations to the possible outcomes are as follows;

If β_2 is above zero as in ($\beta_2 > 0$), and π is below as in ($\pi < 0$), it implies, the relationship between income and ecological pollution is inverted U-shaped validating the EKC conjuncture.

If β_2 is below zero as in ($\beta_2 < 0$) and π is above zero as in ($\pi > 0$), it means, the association between income and ecological pollution is U-shaped.

If both β_2 and π are equal to zero ($\beta_2 = \pi = 0$), it implies, there is no relationship between income and environmental contamination.

If β_2 is greater than zero ($\beta_2 > 0$) and π is equal to zero ($\pi = 0$), it implies, the rise in income leads to a rise in ecological deterioration.

Finally, if β_2 is less than zero ($\beta_2 < 0$) and π is equal to zero ($\pi = 0$), it means a decrease in income leads to an increase in environmental pollution.

3.3 | Econometric Strategy

Trade and other macroeconomic indicators might cause cross-sectional dependence (CD) amongst panel units. This issue should be seriously accounted for in panel regression analysis because it might result in erroneous estimates and conclusions. Therefore, as a first step, we test for CD across the residual terms via the Breusch-Pagan LM, Peseran scaled LM, and Peseran CD tests. Also, because the ignorance of heterogeneity in the slope parameters might lead to biased results, we test for slope heterogeneity or homogeneity through the Pesaran and Yamagata (2008) method. The test predicts two statistics as follows;

$$\text{Delta tilde}\left(\widetilde{\Delta}\right) = \sqrt{N}\left(\frac{N^{-1}\widetilde{S} - k}{\sqrt{2k}}\right) \tag{8}$$

$$\text{Adjusted delta tilde}\left(\widetilde{\Delta}_{\text{adj}}\right) = \sqrt{N}\left(\frac{N^{-1}S - E(\widetilde{z}_{iT})}{\sqrt{\text{Var}(\widetilde{z}_{iT})}}\right) \tag{9}$$

Since homogeneity in slope parameters is the premises of the test, the rejection of this basic assumption would then imply that the slope coefficients are heterogeneous. Moreover, variables' integration order is essential in regression analysis because they guide the choice of econometric methods to be used. Therefore, at the third stage, the CIPS and CADF unit root tests that account for CD in panel units are used to assess the integration features of the series. The CADF test is expressed as;

$$\Delta y_{it} = a_i + b_i y_{i,t-1} + c_i \overline{y}_{t-1} + \sum_{j=0}^{p} d_{ij}\, \Delta \overline{y}_{t-j} + \sum_{j=1}^{p} \delta_{ij}\, \Delta y_{i,t-j} + e_{it} \tag{10}$$

In the above model, the cross-sectional averages are denoted by $\overline{y}_{t-j}$ and $\Delta\overline{y}_{t-j}$ and getting the averages of Equation (10) will provide the CIPS test expressed as;

$$\text{CIPS} = N^{-1} \sum_{i=1}^{N} \text{CADF}_i \tag{11}$$

The above test's the null hypothesis of nonstationarity as against the alternative hypothesis of stationarity. Furthermore, macroeconomic shocks might lead to structural breaks in panel units. This implies, failure to account for structural breaks might result in misleading estimates and inferences. Therefore, the Bai and Carrion-i-Silvestre (2009) test that is robust to the above issue is also performed to examine the variables' integration properties. The test is specified as;

$$y_{it} = \alpha_i + F_t' \pi_i + \sum_{j=1}^{li} \theta_{ik} \text{DU}_{ikt} + \beta_i t + \sum_{k=1}^{mi} \gamma_{ik} \text{DT}_{ikt} + \varepsilon_{it} \tag{12}$$

where, the j alongside k are respectively the dates for the breaks at levels and trend; l_i and mi are the structural breaks affecting the mean and the trend correspondingly; F_t and π_i are common factors as well as factor loadings in that order; and DU and DT are the dummy variables. Moreover, the test for cointegration is pertinent because it gives the green light for the parameters of predictors to be estimated. Therefore, at the fourth stage, the Westerlund's (2007) test, which controls for residual CD is engaged to determine whether the series possess a long-run cointegration association or not. The test is specified as;

$$\Delta z_{it} = \delta_i' d_i + \theta_i \left(z_{i(t-1)} + \pi_i'\right) + \sum_{j=1}^{m} \theta_i \Delta z_{i(t-1)} + \sum_{j=1}^{m} \varphi_i \Delta y_{i(1-j)} + \omega_{it} \tag{13}$$

where θ_i captures the adjustment speed to the equilibrium. The test encompasses a group $\left(G_\tau, G_\alpha\right)$ and a panel $\left(P_\tau, P_\alpha\right)$ statistics expressed as;

$$G_\tau = \frac{1}{N} \sum_{i=1}^{N} \frac{\theta_i}{SE\left(\widehat{\theta}_i\right)} \tag{13a}$$

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

$$P_\tau = \frac{\widehat{\theta}_i}{SE\left(\widehat{\theta}_i\right)} \tag{13c}$$

$$P_\alpha = T\widehat{\theta}_i \tag{13d}$$

The test's null hypothesis is no cointegration within the series. Failure to validate this assumption implies the series possess a long-run cointegration association. The method faces some pitfalls as it overlooks structural breaks. Hence, the test of Banerjee and Carrion-i-silvestre (2017), which is robust to structural breaks is also adopted to assess the cointegration features of the series. The aforestated test is expressed as;

$$Y_{it} = \partial_i + G_t' \emptyset_i + \omega_i D_{it} + \delta_{it} + X_{it}' u_i + \left(D_{it} X_{iT}\right)' \vartheta_i + \varepsilon_{it} \tag{14}$$

where $D_{it} = 1\left(t > T_i\right)$; Y_{it} and X_{it} are the output and input variables correspondingly; T_i is the date of the break; and ε_{it} and ∂_i are respectively the error and constant terms. After affirming cointegration among the series, we first engage the DCCEMG technique to estimate the elasticities of the predictors. This method helps to reduce CD by proxying unobserved common factors with cross-sectional means of observables in a regression (Cao and Qiankun 2022). It is also robust to heterogeneity, endogeneity, and nonstationary common factors (Chudik and Pesaran 2015). The DCCEMG specification of the baseline model is specified as;

$$\begin{aligned} \ln GHG_{it} = {} & \kappa_i + \phi_i \ln GHG_{i,t-1} + \delta_1 \ln POP_{i,t} + \delta_2 \ln GDP_{i,t} \\ & + \delta_3 \ln GF_{i,t} + \delta_4 \ln FDI_{i,t} + \delta_5 \ln NRE_{i,t} \\ & + \delta_6 \ln ICT_{i,t} + \delta_7 \ln FD_{i,t} + \sum_{j=0}^{p_T} \psi_{1j} \overline{\ln GHG_{i,t-1}} \\ & + \sum_{x=0}^{p_T} \psi_{2j} \overline{\ln POP_{i,t}} + \sum_{x=0}^{p_T} \psi_{3j} \overline{\ln GDP_{i,t}} \\ & + \sum_{x=0}^{p_T} \psi_{4j} \overline{\ln GF_{i,t}} + \sum_{x=0}^{p_T} \psi_{5j} \overline{\ln FDI_{i,t}} \\ & + \sum_{x=0}^{p_T} \psi_{6j} \overline{\ln NRE_{i,t}} + \sum_{x=0}^{p_T} \psi_{7j} \overline{\ln ICT_{i,t}} \\ & + \sum_{x=0}^{p_T} \psi_{8j} \overline{\ln FD_{i,t}} + \mu_{it} \end{aligned} \tag{15}$$

where p_T represents the cross-sections' mean lags; $\overline{\ln GHG_{i,t-1}}$, $\overline{\ln POP_{i,t}}$, $\overline{\ln GDP_{i,t}}$, $\overline{\ln GF_{i,t}}$, $\overline{\ln FDI_{i,t}}$, $\overline{\ln NRE_{i,t}}$, $\overline{\ln ICT_{i,t}}$, and $\overline{\ln FD_{i,t}}$, are the cross-sectional means and $\psi_{1,\dots,}\psi_8$ are their corresponding coefficients. To test whether the results are consistent over methodologies, the AMG and CCEMG estimates are also explored. This technique is beneficial because it is efficient to panels flanked with heterogeneity and CD (Eberhardt 2012). It also controls for endogeneity, and weak cointegration among the series (Erdogan, Okumus, and Guzel 2020). Besides, the AMG is suitable for models with stationary or nonstationary variables. Moreover, when the panel under consideration is unbalanced like our case, the AMG approach can still be applied (Işik et al. 2020). A two-staged process is used to conduct the AMG estimation. Using the baseline model (Model A) as an instance, Equation (4) is specified in a T–1 dummies and first differenced form as;

$$\begin{aligned} \Delta \ln GHG_{it} = {} & \alpha_i + \beta_1 \Delta \ln POP_{it} + \beta_2 \Delta \ln GDP_{it} + \beta_3 \Delta \ln GF_{it} \\ & + \beta_4 \Delta \ln FDI_{it} + \beta_5 \Delta \ln NRE_{it} + \beta_6 \Delta \ln ICT_{it} \\ & + \beta_7 \Delta \ln FD_{it} + \sum_{t=2}^{T} \emptyset_t (\Delta D_t) + \varepsilon_{it} \end{aligned} \tag{16}$$

where $\emptyset_t$ is the coefficient of the first difference order of T–1 dummies ΔD_t. At the second stage, a common dynamic process is formed by converting $\emptyset_t$ to $P_t(\emptyset_t = P_t)$ as follows;

$$\begin{aligned} \Delta GHG_{it} = {} & \alpha_i + \beta_1 \Delta POP_{it} + \beta_2 \Delta GDP_{it} + \beta_3 \Delta GF_{it} \\ & + \beta_4 \Delta FDI_{it} + \beta_5 \Delta NRE_{it} + \beta_6 \Delta ICT_{it} \\ & + \beta_7 \Delta FD_{it} + P_t(d_t) + \varepsilon_{it} \end{aligned} \tag{17}$$

$$\begin{aligned} \Delta GHG_{it} - P_t(d_t) = {} & \alpha_i + \beta_1 \Delta POP_{it} + \beta_2 \Delta GDP_{it} \\ & + \beta_3 \Delta GF_{it} + \beta_4 \Delta FDI_{it} \\ & + \beta_5 \Delta NRE_{it} + \beta_6 \Delta ICT_{it} \\ & + \beta_7 \Delta FD_{it} + \varepsilon_{it} \end{aligned} \tag{18}$$

where d_t is the dynamic process. Based on above models, the elasticities of the determinants are correspondingly estimated as;

$$\beta_{1,AMG} = \frac{1}{N} \sum_{i=1}^{N} \beta_{1i}, \beta_{2,AMG} = \frac{1}{N} \sum_{i=1}^{N} \beta_{2i}, \beta_{3,AMG} = \frac{I}{N} \sum_{i=1}^{N} \beta_{3i}, \beta_{4,AMG} = \frac{I}{N} \sum_{i=1}^{N} \beta_{4i},$$
$$\beta_{5,AMG} = \frac{I}{N} \sum_{i=1}^{N} \beta_{5i}, \beta_{6,AMG} = \frac{I}{N} \sum_{i=1}^{N} \beta_{6i}, \beta_{7,AMG} = \frac{I}{N} \sum_{i=1}^{N} \beta_{7i} \tag{19}$$

Just like the AMG, the CCEMG technique is also efficient to CD as well as heterogeneity in slope. It also controls for endogeneity (Damette and Marques 2019), and can estimate the elasticities of the individual cross-sectional units (Murshed, Khan, and Rahman 2022). Related to the baseline model, the CCEMG specification of the study is expressed as;

$$\begin{aligned} GHG_{it} = {} & \kappa_i + \delta_1 \ln POP_{it} + \delta_2 GDP_{it} + \delta_3 GF_{it} \\ & + \delta_4 FDI_{it} + \delta_5 NRE_{it} + \delta_6 ICT_{it} + \delta_7 FD_{it} \\ & + \pi_1 \overline{\ln POP_{it}} + \pi_2 \overline{\ln GDP_{it}} + \pi_3 \overline{\ln GF_{it}} \\ & + \pi_4 \overline{\ln FDI_{it}} + \pi_5 \overline{\ln NRE_{it}} + \pi_6 \overline{\ln ICT_{it}} \\ & + \pi_7 \overline{\ln FD_{it}} + \varepsilon_{it} \end{aligned} \tag{20}$$

In the above specification, the cross-sectional averages are denoted by $\overline{\ln POP_{it}}$, $\overline{\ln GDP_{it}}$, $\overline{\ln GF_{it}}$, $\overline{\ln FDI_{it}}$, $\overline{\ln NRE_{it}}$, $\overline{\ln ICT_{it}}$ and $\overline{\ln FD_{it}}$; and $\pi_1 \dots \pi_7$ are their corresponding coefficients. Also, ε_{it} and κ_i are the error and constant terms of country i in time t respectively, while $\delta_1 \dots \delta_7$ are the unestimated coefficients of the predictors. Besides, the affirmation of long-run relationship among the series does not guarantee causation. Therefore, at the final stage, the Dumitrescu and Hurlin (2012) causality test is engaged to explore the causalities between the variables. This test is considered over other causality techniques because it is robust to heterogeneous panels like that of this study. The model of the above test is expressed as;

$$Y_{it} = w_i + \sum_{m=1}^{M} \alpha_i^{(m)} Y_{it-m} + \sum_{m=1}^{M} \delta_i^{(m)} X_{it-m} + \varepsilon_{it} \tag{21}$$

where Y_{it} and X_{it} are correspondingly the regressand and the regressors of country i in time t; w_i is the constant term; M denotes the lags; and $\alpha_i^{(m)}$ represent the autoregressive coefficients. The test comes out with two statistics specified as;

$$W_{N,T}^{HNC} = N^{-1} \sum_{i=1}^{N} W_{i,t} \tag{22}$$

$$Z_{N,T}^{HNC} = \frac{\frac{1}{\sqrt{N}} \left[\sum_{i=1}^{N} W_{i,t} - \sum_{i=1}^{N} E(W_{i,t}) \right]}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} \mathrm{Var}(W_{i,t})}} \tag{23}$$

where $Z_{N,T}^{HNC}$ denotes the Z-bar statistic, $W_{N,T}^{HNC}$ represents the W-statistic, and $\mathrm{Var}(W_{i,t})$ and $E(W_{i,t})$ are its variance and expectations. The test looked at the null hypothesis absence of causal link as against its presence. The flowchart showing the summary of the methodological approaches of the study is shown in Figure 2.

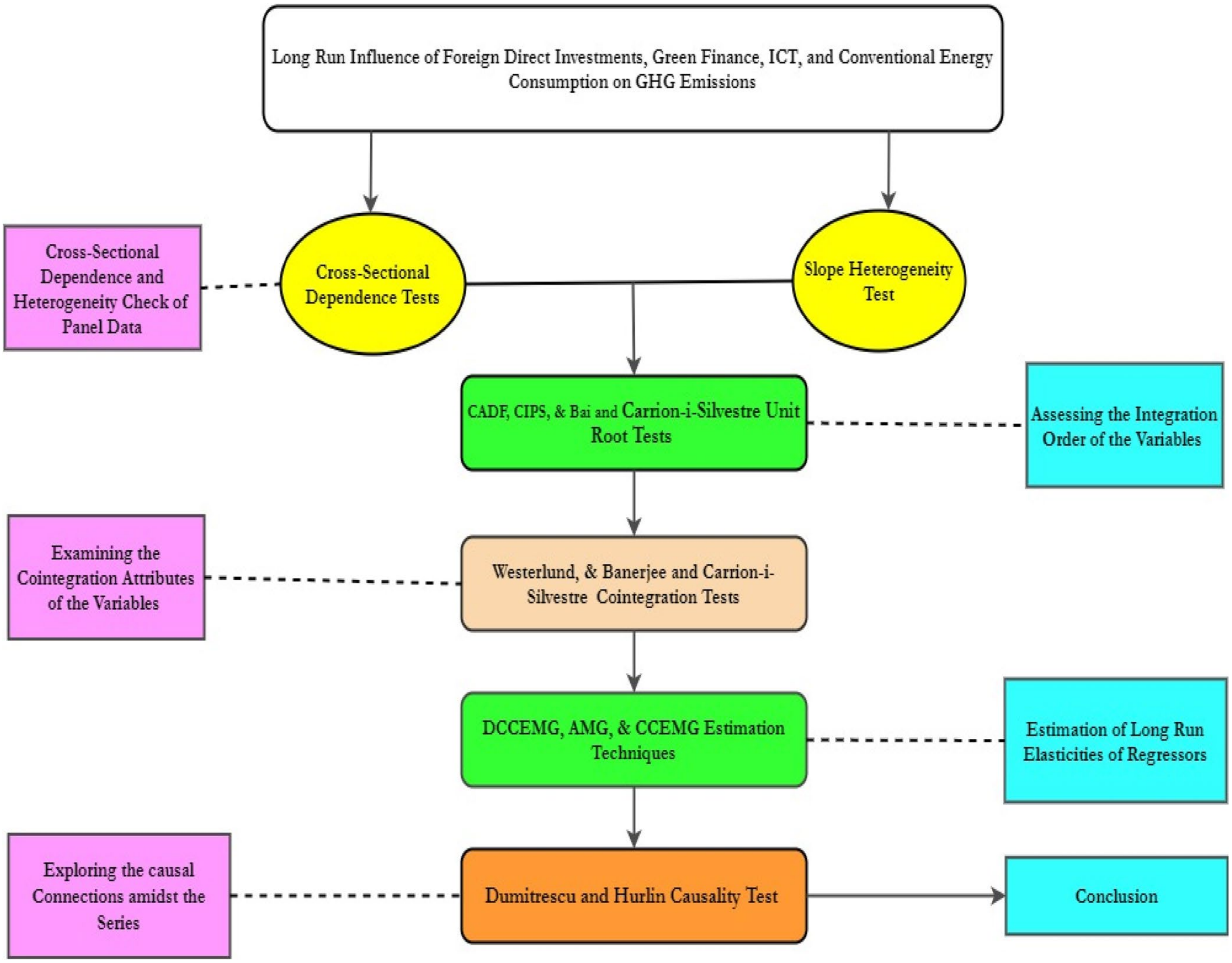

FIGURE 2 | Flowchart showing the methodological approach of the study.

TABLE 4 | Descriptive statistics.

	LnGHG	LnPOP	LnGDP	LnGF	LnFDI	LnNRE	LnFD
Mean	10.44	1.12	7.46	4.35	1.18	2.82	3.86
Median	10.77	1.13	7.52	4.38	1.29	3.16	3.72
Maximum	11.37	1.42	9.101	4.59	3.69	3.88	8.33
Minimum	9.13	0.85	5.78	3.88	−3.83	0.49	1.42
Std. Dev.	0.80	0.13	0.98	0.17	1.30	0.96	0.87
Skewness	−0.26	0.03	−0.11	−0.66	−1.07	−1.31	1.99
Kurtosis	1.33	2.28	2.22	2.78	5.36	3.31	12.60
Jarque-Bera	9.31	1.60	1.99	5.47	30.76	21.05	328.35
Probability	0.00	0.45	0.37	0.07	0.00	0.00	0.00

4 | Results and Discussion

4.1 | Descriptive Statistics and Correlational Analysis

Table 4 shows the descriptive statistics and variability of the data. From the results, the mean and median values for LnGHG are around 10.44 and 10.77, respectively, suggesting that the average and middle values of greenhouse gas emissions in the region are relatively high. The standard deviation for LnGHG is 0.80, and implies that the data points are relatively close to the mean, indicating moderate variability in greenhouse gas emissions. The average financial development level (mean LnFD) in Central African nations is around 3.86.

However, the distribution of LnFD is positively skewed, indicating that a few countries may have higher financial development levels than the majority. On average, the level of green investment (LnRE) in Central African nations is around 4.35. The distribution of LnRE values shows a slight negative skewness and moderate kurtosis, indicating a moderately peaked distribution with heavier tails.

4.2 | Cross-Sectional Dependence and Heterogeneity Analysis

Table 5 presents the cross-sectional dependence. The results in both Panel A and B significantly suggest substantial cross-sectional dependence and heterogeneity in the data. In this regard, a change in one factor in one nation will affect other factors in other countries. These findings have implications for the analysis and interpretation of the panel data, emphasizing the importance of accounting for cross-sectional dependence and heterogeneity in the statistical modeling and generalization of the results.

4.3 | Unit Root Analysis

Table 6 shows the unit root results from CIPS and CADF. The evidence from both the CIPS and CADF tests affirms non-stationarity at *I*(0). However, after taking the first difference,

TABLE 5 | Results for the CD and heterogeneity analyses.

Panel A: Methods	For the Model-1	For the Model-2	For the Model-3	For the Model-4
Breusch-Pagan LM	18.92 (0.000)***	12.96 (0.000)***	15.27 (0.000)***	13.48 (0.000)***
Pesaran scaled LM	11.10 (0.000)***	9.67 (0.020)**	10.63 (0.000)***	11.26 (0.000)***
Pesaran CD	8.79 (0.020)**	10.17 (0.000)***	8.17 (0.030)**	10.11 (0.000)***
Panel B: Heterogeneity test				
$\tilde{\Delta}$-tilde stat.	10.17 (0.00)***	11.02 (0.00)***	9.15 (0.02)**	13.97 (0.00)***
$\tilde{\Delta}_{adj}$-tilde stat.	14.88 (0.00)***	16.15 (0.00)***	12.24 (0.00)***	17.08 (0.00)***

Note: Values in parenthesis () denote probabilities, ***, ** indicate significance at the 1% and 5% levels respectively.

TABLE 6 | The results for CIPS and CADF tests.

	Using CIPS		Using CADF	
The variables	At levels	At 1st difference	At levels	At 1st difference
lnGHG	−2.51	−5.78***	−2.34	−5.83***
lnPOP	−1.34	−3.45**	−1.75	−4.86***
lnGDP	−2.07	−4.21***	−2.31	−5.79***
lnGF	−2.14	−4.42***	−2.05	−5.54***
lnFDI	−1.38	−3.64**	−1.67	−3.83***
lnNRE	−2.22	−5.57***	−1.81	−4.91***
lnICT	−1.31	−3.35**	−1.55	−3.58**
lnFD	−1.82	−3.84***	−2.15	−5.62***
lnFD × lnGF	−2.12	−4.38***	−1.94	−4.98***
lnFD × lnFDI	−1.44	−3.74**	−2.23	−5.70***
lnFD × lnNRE	−2.36	−5.75***	−2.51	−5.97***
lnFD × lnICT	−1.22	−3.25**	−1.47	−3.51**
$lnGF^2$	−1.77	−3.81***	−1.87	−4.94***
$lnFDI^2$	−2.05	−4.18***	−1.56	−3.62**
$lnNRE^2$	−2.18	−4.46***	−2.24	−5.72***
$lnICT^2$	−1.19	−3.18**	−1.42	−3.47**
$lnGDP^2$	−1.65	−3.76**	−1.66	−3.78**

Note: The triple * and the double * show significance at the 1% and 5% levels accordingly.

all variables become stationary, suggesting that the variables possess a stochastic trend or unit root but exhibit a stable behavior after accounting for the changes or differences between consecutive observations. Table 7 shows the Bai and Carrion-i-Silvestre (2009) unit root results and confirms the earlier results using the CIPS and CADF. All the variables are non-stationary at the level but significant at the first difference. These findings imply that further analysis and modeling using stationary time series techniques would be appropriate.

4.4 | Cointegration Analysis

Table 8 presents the results for the long-term connection among the variables tested. In Panel A, the Westerlund (2007) test statistics are reported for the models (i.e., Model-1, Model-2, Model-3, and Model-4) and variables (Gt, Ga, Pt, and Pa). The test statistics for all models and variables are highly significant, implying a long-term relationship exists between them. In Panel B, the Banerjee and Carrion-i-Silvestre (2017) test results are provided for different countries (Angola, Cameroon, Congo Republic, Congo DR, Gabon). Like Panel A, the test statistics for all models and countries are highly significant, suggesting cointegration among the variables within each country. These findings imply the need for further analysis and modeling to understand the long-term dynamics and relationships among the variables.

4.5 | Regression Analysis

4.5.1 | Direct Effects

Table 9 shows the DCCEMG technique's results by considering time dynamics, cross-sectional dependence, and individual heterogeneity. Model 1 presents the linear effects results of our explanatory variable on greenhouse gas. First, a significant relationship exists between the previous period's level and the current GHG emissions, with an estimated elasticity parameter of −0.82. This finding indicates a negative autocorrelation in GHG emissions over time, contradicting the evidence from a previous study (Gricar, Bojnec, and Baldigara 2022). Also, an increase in population raises greenhouse gas emissions by 0.95%. The finding means in Central Africa, where access to modern energy sources is limited, population growth increases reliance on traditional and inefficient energy sources such as biomass for cooking and heating purposes ultimately increasing GHG emissions. According to Opoku-Mensah et al. (2021), population growth often coincides with increased economic activities and industrialization such that as the population expands, there is a higher demand for goods and services, leading to increased industrial production and eventually contributing to GHG emissions. This finding aligns with Teklie and Yağmur (2024) who confirmed population growth as harmful to environmental quality in Africa. The finding also supports Ahmed et al. (2023) who

TABLE 7 | Bai and Carrion-i-Silvestre (2009) unit root test.

	Levels			1st difference		
Variables	***Z* statistic**	**Pm statistic**	***P* statistic**	***Z* statistic**	**Pm statistic**	***P* statistic**
lnGHG	0.65	−0.91	38.55	−3.81***	4.92***	68.57***
lnPOP	0.42	−0.72	41.02	−3.65***	4.65***	76.52***
lnGDP	0.77	−0.85	43.58	−3.87***	4.87***	77.41***
lnGF	0.46	−0.64	37.62	−3.72***	2.88***	67.34***
lnFDI	0.95	−0.97	44.17	−3.98***	4.96***	78.58***
lnNRE	0.58	−0.83	36.34	−3.79***	4.85***	66.82***
lnICT	0.48	−0.71	33.41	−3.76***	4.63***	55.65**
lnFD	0.45	−0.75	34.82	−3.71***	4.77***	55.71**
lnFD × lnGF	0.61	−0.96	43.71	−3.80***	4.94***	77.47***
lnFD × lnFDI	0.47	−0.74	37.86	−3.74***	4.75***	67.45***
lnFD × lnNRE	0.73	−0.98	41.93	−3.85***	4.98***	76.54***
lnFD × lnICT	0.25	−0.70	33.40	−1.58*	4.62***	55.62**
$lnGF^2$	0.34	−0.55	−35.16	−2.31**	2.74***	65.62***
$lnFDI^2$	0.72	−0.62	−33.42	−3.82***	2.87***	55.68**
$lnNRE^2$	0.56	−0.73	−40.41	−3.78***	4.68***	75.57***
$lnICT^2$	0.21	−0.69	33.38	−1.44*	4.61***	55.54**
$lnGDP^2$	0.28	−0.56	−37.83	−2.24**	2.71***	67.41***

Notes: The triple * and the double * show significance at the 1% and 5% levels accordingly.

TABLE 8 | Long-run cointegration.

Panel A: Westerlund (2007) test				
Stat.	**The Model-1**	**The Model-2**	**The Model-3**	**The Model-4**
For Gt	−5.57 (0.00)***	−4.87 (0.00)***	−5.75 (0.00)***	−4.93 (0.00)***
For Ga	−6.71 (0.00)***	−5.43 (0.00)***	−6.62 (0.00)***	−5.86 (0.00)***
For Pt	−4.65 (0.02)***	−3.14 (0.03)**	−3.31 (0.02)**	−4.95 (0.00)***
For Pa	−6.84 (0.00)***	−5.71 (0.00)***	−4.85 (0.00)***	−5.07 (0.00)***
Panel B: Banerjee and Carrion-i-Silvestre (2017) approach				
Panel	**The Model-1**	**The Model-2**	**The Model-3**	**The Model-4**
Angola	−5.84***	−4.78***	−5.57***	−4.92***
Cameroon	−4.75***	−5.21***	−4.94***	−5.07***
Congo Republic	−2.92**	−3.75***	−3.51***	−4.11***
Congo DR	−5.68***	−2.87**	−5.66***	−3.12***
Gabon	−5.47***	−4.45***	−3.93***	−4.51***

Note: The triple * and the double * show significance at the 1% and 5% levels accordingly.

affirmed population as a positive determinant of environmental pollution in India. However, Mohammed et al. (2024) confirmed population is friendly to the environment of the European Union while Ahmad, Wahyudi, and Lestari (2024) reported an insignificant relationship between population and environmental pollution in Indonesia. These discoveries contradict the outcome of this study.

Besides, an increase in lnGDP increases greenhouse gas emissions by 1.66%. As agriculture plays a crucial role in the economies of Central African countries, our findings explain that the method of farming is unsustainable and contributing to deforestation, soil degradation, and emissions. According to Lu (2017), developing economies rely on older and more polluting technologies, contributing to GHG emissions. As reported by Opoku-Mensah et al. (2021) and Zambrano-Monserrate et al. (2020), society will be permanently destroyed if unsustainable economic activities continue. This finding supports Espoir, Sunge, and Bannor (2023) who confirmed economic growth as harmful to environmental quality in Africa. However, Donkor et al. (2022) disclosed an insignificant relationship between economic growth and environmental degradation in North Africa, contrasting the outcome of this investigation.

Moreover, green investment decreases greenhouse gas by 0.93%. This is not surprising because green investment supports advancement in energy-efficient technologies by upgrading existing infrastructure, improving energy management systems, and adopting energy-saving measures in industries, buildings, and transportation (Cao 2023; Fatica and Panzica 2021). According to Cao (2023), one way to promote environmental quality is for policymakers to implement green financing reforms to promote the adoption of efficient technologies. The research of Antwi, Kong, and Donkor (2024) affirmed green investment as friendly to environmental quality in African economies thereby supporting the outcome of this study. However, Mumuni and Hamadjoda Lefe (2023) reported that in the short run, climate-related development finances, mitigation-related development finances, and adaptation-related development finances worsen environmental quality in Africa. This discovery contradicts the findings of this study.

Meanwhile, lnFDI increases emissions by 1.65% validating the pollution haven hypothesis for the region. According to Hakimi and Hamdi (2016), trade liberalization leads multinational corporations from more developed economies to relocate their low-quality production to developing countries, such as those in Africa, where environmental regulations are less stringent. According to Hu et al. (2021), the weaknesses in environmental regulations among developing nations make them attractive destinations for industries that want to avoid the costs associated with implementing pollution control measures. Previous studies have confirmed the pollution haven hypothesis among developing nations (Opoku-Mensah et al. 2021; Wang et al. 2021). This finding aligns with Kwablah (2023) and Amoah, Alagidede, and Sare (2023) who confirmed FDI as harmful to environmental quality in Sub-Saharan Africa but contradicts Limazie and Woni (2024) who affirmed the variable as a negative determinant of emissions in the ECOWAS region.

Likewise, lnNRE significantly raises emissions by 0.85%. This implies, the reliance on fossil fuels such as coal, oil, and natural gas for energy needs negatively contributes to carbon emissions. Existing studies (Achuo, Miamo, and Nchofoung 2022; Deng et al. 2020) have found evidence to confirm how the burning of fossil fuels in the oil extraction process and the use of oil-based energy for electricity generation result in substantial CO_2 emissions. This finding supports Jiying, Beraud, and Xicang (2023) and Khan et al. (2023) both for Africa, but contrasts Diallo (2024) for Sub-Saharan Africa.

Additionally, lnICT mitigates GHG emissions by 1.13%, indicating that higher levels of ICT development tend to enhance environmental quality in the region. The finding also suggests

TABLE 9 | DCCEMG estimation results.

Dependent variable = greenhouse gas (GHG) emissions				
Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
L.lnGHG	−0.82 (0.00)***	−0.82 (0.00)***	−0.86 (0.00)***	−0.71 (0.00)***
lnPOP	0.95 (0.00)***	0.76 (0.00)***	0.87 (0.00)***	0.75 (0.00)***
lnGDP	1.66 (0.00)***	1.82 (0.00)***	1.55 (0.00)***	1.50 (0.00)***
lnGF	−0.93 (0.00)***	−0.71 (0.00)***	−0.77 (0.00)***	−0.94 (0.00)***
lnFDI	1.65 (0.00)***	0.58 (0.04)**	0.61 (0.03)**	1.05 (0.00)***
lnNRE	0.85 (0.00)***	0.79 (0.00)***	0.82 (0.00)***	0.63 (0.03)**
lnICT	−1.13 (0.00)***	−1.81 (0.00)***	−1.14 (0.00)***	−1.05 (0.00)***
lnFD	0.75 (0.00)***	0.42 (0.05)*	0.68 (0.02)**	0.74 (0.00)***
lnFD × lnGF	—	−2.66 (0.00)***	—	—
lnFD × lnFDI	—	0.97 (0.00)***	—	—
lnFD × lnNRE	—	0.85 (0.00)***	—	—
lnFD × lnICT	—	0.54 (0.05)*	—	—
ln GF^2	—	—	−1.44 (0.00)***	—
$lnFDI^2$	—	—	−0.11 (0.00)***	—
$lnNRE^2$	—	—	0.85 (0.00)***	—
$lnICT^2$	—	—	−0.94 (0.00)***	—
$lnGDP^2$	—	—	—	−0.10 (0.00)***
F-statistic	54.12 (0.00)***	66.75 (0.00)***	72.94 (0.00)***	59.16 (0.00)***
R-squared (R^2)	0.75	0.87	0.84	0.77
Adjusted R^2	0.71	0.83	0.80	0.73
RMSE	0.05	0.02	0.03	0.04
CD-statistic	−4.47 (0.12)	−1.24 (0.14)	−2.15 (0.56)	−3.82 (0.55)

Note: The triple * and the double * show significance at the 1% and 5% levels accordingly.

that the swift adoption of the internet in conjunction with widespread mobile cellular subscriptions is leading to the production of energy-efficient ICT devices in Central Africa. As highlighted by Godil et al. (2020), using ICT to manage and optimize energy distribution and consumption minimizes energy waste and reduces carbon emissions. To Ke et al. (2022), the use of ICT enhances environmental quality as it positively contributes to reducing emissions. Evans and Mesagan (2022) confirmed ICT as beneficial to the environment in Africa, aligning with the findings of this study. However, the investigations of Onyeneke, Chidiebere-Mark, and Ayerakwa (2024) and Ganda (2024) contrast this finding as they confirmed ICT as harmful to environmental quality in Africa.

Finally, lnFD positively predicts GHG emissions by 0.75%. The positive lnFD-GHG link shows that as financial development increases, so does the level of GHG emissions. Sadorsky (2010) has attributed this increasing effect to the facilitation of expanded financing channels, which enable enterprises to obtain capital at lower costs, leading to the scaling up of production, such as acquiring additional equipment and establishing new production lines, potentially resulting in higher carbon emissions. According to Obobisa (2022), with an increased financial system in developing economies, industries that heavily rely on fossil fuels, such as manufacturing and construction may expand their operations, leading to more energy use and subsequent GHG emissions. Likewise, Brown et al. (2022) found that financial sector's expansion may increase reliance on carbon-intensive construction materials or fossil fuel-based energy sources in newly built facilities and can raise emissions levels. This finding is in tandem with the studies of Chen, Manu, and Asante (2023) for 34 African economies and Horobet et al. (2024) for the European Union, but deviates from Prempeh (2024) for the ECOWAS region and Antwi, Kong, and Donkor (2024) for Southern Africa.

4.5.2 | Interaction Effects of the Explanatory Variable With FD

Table 9, Model 2 shows the interaction effects of financial development with the explanatory variable on GHG. First, a significant negative coefficient (−2.66) has been found for the combined effects of financial development and green investment ln(FD × GF) on GHG. Thus, financial development alone increase emissions but, when combined with green investment, mitigates emissions. This suggests that the integration of financial development and green investment within Central African Countries will channel investment and funding towards renewable energy projects energy-efficient technologies and, reduce reliance on fossil fuels and subsequently lowering greenhouse gas emissions. This outcome aligns with the assertion of Saeed Meo and Karim (2022) that green investment channels provide the necessary resources and incentives to support low-carbon initiatives. The finding also agrees with Zhang et al. (2022) who opined that the mechanism of green investment redirects financial flows towards environmentally sustainable projects, which can lead to emissions reduction and the adoption of cleaner technologies. According to Chen and Majeed (2024), financial development does not promote green investments in Africa. This contradicts the outcome of this study.

Also, the interaction effects of financial development and FDI raised greenhouse gas emissions in the region. This finding implies when financial institutions that have operated in carbon-intensive industries or regions bring their expertise and investment strategies to new markets, it encourages the replication of unsustainable practices that contribute to increased greenhouse gas emissions. The evidence suggests a need for policymakers to foster partnerships between local financial institutions and international development agencies that specialize in sustainable finance. The finding contradicts the view of Prempeh (2024) that development in the financial sector enhances environmental quality by stimulating FDIs linked to research and development initiatives. The finding also contrasts Yiadom, Mensah, and Bokpin (2022) who reported that FDI worsens environmental quality in 45 Sub-Saharan African countries but when FDI is moderated with financial sector development it enhances environmental sustainability. In the study of Udeagha and Breitenbach (2023), financial development negatively moderated the relationship between FDI and environmental pollution in South Africa. This deviates from the outcome of this investigation.

Similarly, the interaction effect of financial development and non-renewable energy raises greenhouse gas emissions by 0.85. One key explanation is the reliance on fossil fuel investments driven by financial development. Existing studies have confirmed how institutions may support the development of non-renewable energy projects, such as oil, gas, and coal, raising emissions (Ali, Jianguo, and Kirikkaleli 2023). According to Ali, Jianguo, and Kirikkaleli (2023), policymakers can establish mechanisms to discourage investments in non-renewable energy projects with high carbon footprints by utilizing carbon-pricing approaches to include but not limited to carbon taxes as well as cap & trade systems. This discovery supports Ehigiamusoe et al. (2022) who reported that the interaction between financial development and energy consumption harmed environmental quality by raising pollutant emissions in 31 African economies. The finding also aligns with Udeagha and Breitenbach (2023) who confirmed the interactive effects of financial development and energy consumption as damaging to environmental quality in South Africa. As reported by Chiu and Zhang (2023), well-developed financial systems promote the beneficial environmental effects of renewable energy contrasting the outcome of this investigation.

Likewise, financial development and ICT's combined effects raise emissions by 0.55%. This outcome is justifiable because the growth in ICT development as a result of the rise in financial institutions increase the need for data centers, network infrastructure, and electronic devices. These components consume substantial amounts of energy, often generated from non-renewable sources, leading to greenhouse gas emissions. The evidence suggests the need for governments to provide financial incentives, tax breaks, and subsidies for renewable energy projects specifically targeted at the ICT sector to reduce the carbon footprint associated with ICT development. This finding supports Ke et al. (2022) who reported that the interaction between financial development and ICT escalated emissions in 77 developing countries. The finding also aligns with the study of Tao, Sheng, and Wen (2023) which disclosed a harmful interactive effect of financial development and ICT in OECD economies. Similarly, Zafar et al. (2022) research on selected Asian economies collaborates this finding as they disclosed a positive relationship between environmental pollution and the interaction between financial development and ICT.

4.5.3 | Quadratic Relationship of Green Investment, FDI, Non-Renewable Energy, ICT, and GDP

Table 9, Model 3 presents the results on the quadratic effects of some key variables on greenhouse gas emissions. First, the results show the quadratic effect of green investment reduces greenhouse gas emissions by 1.44%. The negative coefficient of green investments square implies that beyond a certain point, additional investments in green initiatives can have an amplified impact, resulting in accelerated emission reductions. This can be due to the scaling-up of renewable energy projects, the adoption of innovative green technologies, and the development of sustainable practices across various sectors. According to Saeed Meo and Karim (2022), green investment targets environmentally sustainable industries and encourages the advancement of innovative technologies, particularly those related to low-carbon energy, such as renewable energy technologies. This finding supports Antwi, Kong, and Donkor (2024) and Zhang and Zhao (2024) who affirmed the reducing influence of green investment on environmental pollution in Southern Africa and China correspondingly.

Also, FDI square significantly reduces emissions by 0.11%. As FDI continues to increase beyond a certain threshold, the quadratic effect comes into play, and the relationship between FDI and emissions starts to change. According to Xie, Wang, and Cong (2020); Xie, Ouyang, and Choi (2020), as FDI reaches higher levels, it often brings technological advancements, knowledge transfer, and expertise in sustainable practices. Huang et al. (2022) highlight that economies may shift from importing polluted companies towards cleaner and less carbon-intensive industries as they become more developed and matured. This finding deviates from Manocha (2024) who reported that FDI at the higher level escalated environmental pollution in 14 developing economies. The research of Gök, Ashraf, and Jasinska (2024) also contradicts this outcome as they disclosed an inverted U-shaped relationship between emissions and FDI in 124 economies, suggesting that higher levels of emissions are associated with lower levels of FDI inflows. However, Alshubiri and Elheddad (2020) confirmed an inverted U-shaped relationship between FDI and carbon emissions in OECD economies. This supports the outcome of this study.

Also, the square of NRE has a positive coefficient of 0.85, implying that the association between NRE and environmental pollution is monotonically increasing. This means as non-renewable energy consumption reaches higher levels, the negative externalities associated with its extraction, production, and combustion become more pronounced (Adedoyin et al. 2021; Deng et al. 2020). These negative externalities include air and water pollution, deforestation, habitat destruction, and other forms of environmental degradation. According to Adedoyin et al. (2021), the increasing demand of non-renewable energy resources can lead to more environmentally damaging extraction methods, such as deep-sea drilling or mountaintop removal mining. The linear and quadratic effects of non-renewable energy on GHG emissions within Central African countries highlight the need for urgent action to mitigate environmental degradation. The research of Cheikh, Zaied, and Chevallier (2023) contradicts this finding as they discovered an inverted U-shaped relationship between energy use and CO_2 emissions in the MENA region. However, Idroes et al. (2024) confirmed an increasing effect of conventional energies on environmental pollution aligning with the findings of this study.

Besides, ICT square mitigates emissions by 0.94%, confirming that as ICT infrastructure becomes more advanced and efficient, the energy consumption per unit of output can decrease. In other words, ICT has a monotonically decreasing relationship with environmental pollution in Central Africa. According to Bastida et al. (2019), consistent usage of ICT promotes innovations such as more energy-efficient hardware, optimized data center designs, and improved cooling systems, contributing to energy savings and emission reductions. Confirming this, Shehzad et al. (2022) opine that ICT development enables the implementation of smart grid technologies, intelligent transportation systems, and energy management systems which facilitate more efficient use of energy resources, enable demand-response mechanisms, and promote energy conservation. You, Li, and Waqas (2024) and Li et al. (2023); Li, Zhang, and Zhu (2023) discovered an inverted U-shaped relationship between ICT and emissions in Belt and Road Initiative countries. These findings contrast the outcome of Central Africa. However, Qayyum et al. (2024) affirmed the beneficial environmental influence of ICT in MERCOSUR nations supporting the discovery of this investigation.

Finally, Model 4 validates the EKC hypothesis within our cohort. The results imply that during the initial phase of economic growth which is aligned with the first part of the EKC hypothesis, environmental degradation in Central African nations increases mainly due to the unsustainable practices adopted for such economic growth. However, as they continue to develop, environmental pollution begins to decline due to the implementation of green practices. In this regard, policymakers should implement environmental policies using the EKC assumptions such as investing in renewable energy sources, implementing pollution control technologies, and promoting sustainable resource management (Balsalobre-Lorente et al. 2018). Karim et al. (2022) validated the EKC framework for 30 SSA countries while Barak et al. (2024) confirmed this hypothesis for the Group of Twenty (G20) nations. However, Wang, Li, and Li (2024) confirmed an N-shaped relationship between economic growth and environmental pollution in 214 nations while Yessymkhanova, Azretbergenova, and Saparova (2024) discovered a U-shaped connection among the series in the BRICS. These findings contrast the outcome of this study.

4.6 | Sensitivity Analysis

Sensitivity analysis is conducted to assess the robustness of the results across models and methodologies. First, the study uses ecological footprint as an alternative for GHG emissions (as a response variable) to examine whether the outcomes will be consistent over models or not. Table 10 confirms the earlier results when GHG was used and shows that the coefficients of population, ICT, green finance, financial development, GDP, and nonrenewable remained consistent in terms of direction when greenhouse gas was used. According to Table 10, while ICT and green finance have reducing effects on ecological footprint, population, financial development, FDI, nonrenewable energy and GDP have increasing effects. Regarding the interaction effects, while the $\ln FD \times \ln FDI$, $\ln FD \times \ln NRE$ and $\ln FD \times \ln ICT$ have an increasing effect on ecological footprint, the $\ln FD \times \ln GF$ has a reducing effect on ecological footprint. This evidence is consistent with the evidence when greenhouse gas was used. Again, the results of the quadratic relationship of $\ln GF^2$, $\ln FDI^2$, $\ln ICT^2$ have shown negative coefficients, while that of $\ln NRE^2$ remains positive, confirming the earlier results using greenhouse gas as the dependent variable. The fact that the directions maintain the same suggests that the explanatory power of the independent variables is not specific to GHG emissions alone but extends to ecological footprint as well. These consistent relationships across different environmental indicators provide valuable insights into the drivers of environmental impact and allow policymakers to focus on implementing strategies that target multiple aspects of sustainability.

Secondly, the study employs the AMG and CCEMG techniques to estimate the GHG models to affirm whether the results will be consistent across methodologies or not. Based on the results displayed in Tables 11 and 12, population, financial development, GDP, and nonrenewable increases emissions while ICT, and green finance decrease emissions. The interactive and the nonlinear terms also have the same directions as those under the DCCEMG technique. Consistency of the results under the DCCEMG, AMG, and CCEMG approaches reinforces the reliability and validity of the results and increases confidence in the identified relationships between the independent variables and GHG emissions.

4.7 | Causality Analysis

Table 13 displays the causality results between different variables and greenhouse gas (GHG) emissions within the Central African region. Focusing on unidirectional Causality: Population (lnPOP) has a unidirectional causal effect on GHG

TABLE 10 | DCCEMG estimation results.

	Dependent variable = ecological footprints (EF)			
Variables	Model 1	Model 2	Model 3	Model 4
L.lnGHG	−0.95 (0.00)***	−0.78 (0.00)***	−0.83 (0.00)***	−0.76 (0.00)***
lnPOP	0.87 (0.00)***	0.83 (0.00)***	0.65 (0.02)**	0.78 (0.00)***
lnGDP	0.93 (0.00)***	0.75 (0.00)***	0.79 (0.00)***	1.48 (0.00)***
lnGF	−2.45 (0.00)***	−0.96 (0.00)***	−1.18 (0.00)***	−1.07 (0.00)***
lnFDI	0.78 (0.00)***	1.24 (0.00)***	0.71 (0.00)***	0.85 (0.00)***
lnNRE	1.63 (0.00)***	0.94 (0.00)***	1.22 (0.00)***	0.74 (0.00)***
lnICT	−0.85 (0.00)***	−0.69 (0.02)**	−0.84 (0.00)***	−0.91 (0.00)***
lnFD	1.62 (0.00)***	0.74 (0.00)***	1.76 (0.00)***	0.88 (0.00)***
lnFD × lnGF	—	−1.27 (0.00)***	—	—
lnFD × lnFDI	—	0.65 (0.02)**	—	—
lnFD × lnNRE	—	0.75 (0.00)***	—	—
lnFD × lnICT	—	0.84 (0.00)***	—	—
ln GF^2	—	—	−0.78 (0.00)***	—
lnFDI^2	—	—	−0.13 (0.00)***	—
lnNRE^2	—	—	0.65 (0.02)**	—
lnICT^2	—	—	−0.81 (0.000)***	—
lnGDP^2	—	—	—	−0.12 (0.00)***
F-stat.	64.42 (0.00)***	58.15 (0.00)***	63.65 (0.00)***	59.14 (0.00)***
R-squared (R^2)	0.85	0.77	0.84	0.73
Adjusted R^2	0.81	0.73	0.79	0.69
RMSE	0.01	0.05	0.02	0.06
CD-statistic	−0.54 (0.58)	−1.83 (0.52)	−0.76 (0.74)	−1.91 (0.83)

Note: Values in parenthesis () denote probabilities, *** and ** indicate significance at the 1% and 5% levels respectively.

emissions (lnGHG), with an increase in population leading to higher GHG emissions. Gross domestic product (lnGDP) has a unidirectional causal effect on GHG emissions (lnGHG), indicating that economic growth contributes to increased GHG emissions. Green finance (lnGF) has a unidirectional causal effect on GHG emissions (lnGHG), suggesting that the expansion of green finance is associated with lower GHG emissions. Foreign direct investment (lnFDI) has a unidirectional causal effect on GHG emissions (lnGHG), indicating that higher levels of FDI contribute to increased GHG emissions. Non-renewable energy (lnNRE) has a unidirectional causal effect on GHG emissions (lnGHG), with the use of non-renewable energy sources leading to higher GHG emissions. ICT development (lnICT) has a unidirectional causal effect on GHG emissions (lnGHG), suggesting that advancements in ICT development are associated with lower GHG emissions.

On bidirectional Causality, Financial development (lnFD) and GHG emissions (lnGHG) have a bidirectional causal relationship, meaning that financial development affects GHG emissions, and in turn, GHG emissions also influence financial development. The interaction of financial development and green finance lnFD × lnGF has a bidirectional causal relationship with GHG emissions (lnGHG). The interaction of financial development and foreign investment (lnFD × lnFDI) has a two-way causality with GHG emissions (lnGHG). The interaction of financial development and non-renewable energy lnFD*lnNRE has a bidirectional causal relationship with GHG emissions (lnGHG). The interaction of financial development and ICT development lnFD × lnICT does not exhibit a causal relationship with GHG emissions (lnGHG). These findings indicate the complex interplay between various factors and their effects on GHG emissions in Central African nations. In this regard, efforts should focus on sustainable economic development, promoting green finance, reducing reliance on non-renewable energy sources, and leveraging advancements in ICT to achieve lower GHG emissions and environmental sustainability.

5 | Conclusions and Policy Recommendations

By advancing the emission mitigation agenda of the COP-28, this study examines the influence of financial development in

TABLE 11 | AMG estimation results.

	Dependent variable = greenhouse gas (GHG) emissions			
Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
lnPOP	0.85 (0.00)***	0.69 (0.02)**	0.78 (0.00)***	0.71 (0.00)***
lnGDP	0.74 (0.00)***	0.98 (0.00)***	0.93 (0.00)***	1.82 (0.02)**
lnGF	−0.68 (0.02)**	−0.54 (0.05)*	−0.61 (0.03)**	−0.83 (0.00)***
lnFDI	0.97 (0.00)***	0.37 (0.06)*	0.97 (0.05)*	0.95 (0.00)***
lnNRE	0.64 (0.03)**	0.69 (0.02)**	0.75 (0.00)***	0.42 (0.05)*
lnICT	−0.92 (0.00)***	−0.98 (0.00)***	−0.96 (0.00)***	−0.98 (0.00)***
lnFD	0.67 (0.02)**	0.31 (0.06)*	0.52 (0.05)*	0.65 (0.02)**
lnFD × lnGF	—	−1.85 (0.00)***	—	—
lnFD × lnFDI	—	0.79 (0.00)***	—	—
lnFD × lnNRE	—	0.68 (0.02)**	—	—
lnFD × lnICT	—	0.36 (0.06)*	—	—
ln GF^2	—	—	−0.97 (0.00)***	—
$lnFDI^2$	—	—	−0.22 (0.02)**	—
$lnNRE^2$	—	—	0.71 (0.00)***	—
$lnICT^2$	—	—	−0.82 (0.00)***	—
$lnGDP^2$	—	—	—	−0.14 (0.02)**
Wald-statistic	72.17 (0.00)***	98.55 (0.00)***	87.08 (0.00)***	65.19 (0.00)***
R-squared (R^2)	0.77	0.87	0.84	0.75
RMSE	0.22	0.11	0.15	0.25
CD-statistic	−6.53 (0.47)	−4.18 (0.43)	−5.17 (0.22)	−7.68 (0.51)

Note: Values in parenthesis () denote probabilities; ***, **, * indicate significance at the 1%, 5%, and 10% levels respectively.

mitigation environmental pollution for five Central African nations over the period 1996 to 2019. Moreover, issues of climate finance also resonate as an integral part of the conference discussion to combat the global menace of climate change. Hence, this study assesses roles of green finance, FDI, non-renewable energy intake, and ICT in GHG emission reduction targets while controlling for economic growth and population. The analytical outcomes indicate that, economic growth has a non-linear impact on ecological emission (an inverted U-Shaped curve); the initial outcomes of financial development, non-renewable energy, FDI, and population enhances pollution while green finance and ICT decreases emission for the under study countries. The square of green finance, FDI and ICT decreases pollution level for the Central African nations while square of non-renewable energy intake enhances pollution in the said countries. By interactions with financial development, green finance proof to have positive effect on the environment while FDI, ICT and non-renewable energy enhances pollution levels of the understudy countries. Moreover, the Dumitrescu Hurlin Panel Causality Test utilized reveals that, the is a bidirectional direction between FDI and emission, emission and lnFD*lnGF, emission and lnFD × lnFDI, emissions and lnFD × lnNRE, emission and GF^2, emissions and FDI^2, as well as emission and GDP^2 while the remaining factors has unidirectional connection with emission.

The aforementioned findings give rise to a range of suggestions in view of the quest for SDG-13 attainment. The study posits that Central African nations have the potential to mitigate environmental pollution through the utilization of green finance and information and communication technology (ICT). Initially, by means of the interplay between green finance and sustainability, the governing body can establish a rational oversight framework to ensure sustaınabılıty environmental progress. The implementation of national policy incentives aimed at promoting private investment in sustainable development has the potential to not only mitigate perceived environmental risks but also enhance anticipated returns. The presence of dependable and transparent policies in a market can facilitate the influx of private investment funds, thereby providing investors with greater prospects and motivations. A thorough evaluation of the influence of GF can prove advantageous in gauging its efficacy in promoting "climate and other sustainability goals," thereby furnishing investors with policy stimuli and climate action blueprint. Green finance offers investors the chance to comprehend the sustainability

TABLE 12 | CCEMG estimation results.

	Dependent variable = greenhouse gas (GHG) emissions			
Variables	Model 1	Model 2	Model 3	Model 4
lnPOP	0.76 (0.00)***	0.61 (0.02)**	0.73 (0.00)***	0.67 (0.02)**
lnGDP	0.68 (0.02)**	0.84 (0.00)***	0.67 (0.02)**	1.85 (0.04)**
lnGF	−0.55 (0.04)**	−0.33 (0.06)*	−0.52 (0.05)*	−0.71 (0.00)***
lnFDI	0.83 (0.00)***	0.25 (0.07)*	0.91 (0.07)*	0.86 (0.00)***
lnNRE	0.52 (0.05)*	0.56 (0.04)**	0.65 (0.02)**	0.35 (0.06)*
lnICT	−0.84 (0.00)***	−0.77 (0.00)***	−0.78 (0.00)***	−0.84 (0.00)***
lnFD	0.56 (0.04)**	0.21 (0.07)*	0.34 (0.06)*	0.57 (0.04)**
lnFD × lnGF	—	−0.96 (0.00)***	—	—
lnFD × lnFDI	—	0.62 (0.03)**	—	—
lnFD × lnNRE	—	0.59 (0.04)**	—	—
lnFD × lnICT	—	0.24 (0.07)*	—	—
ln GF^2	—	—	−0.78 (0.00)***	—
lnFDI^2	—	—	−0.15 (0.05)*	—
lnNRE^2	—	—	0.56 (0.04)**	—
lnICT^2	—	—	−0.72 (0.00)***	—
lnGDP^2	—	—	—	−0.13 (0.04)**
Wald-statistic	65.43 (0.00)***	87.98 (0.00)***	79.46 (0.00)***	61.12 (0.00)***
R-squared (R^2)	0.72	0.83	0.81	0.69
RMSE	0.33	0.24	0.26	0.37
CD-statistic	−7.15 (0.56)	−5.86 (0.52)	−6.63 (0.24)	−7.97 (0.89)

Note: Values in parenthesis () denote probabilities; ***, **, * indicate significance at the 1%, 5%, and 10% levels respectively.

performance of potential investments and employ this understanding to initiate a dialogue with the organizations in which they invest. Ultimately, it is recommended that the Global Environment and Climate Agency enhance its regulatory measures pertaining to information disclosure and bolster the efficacy of green finance initiatives. Comprehensive market data and precise and transparent metrics are imperative for bolstering investor assurance in the financial market. Creating an environment that is conducive to business and possessing a strong economic foundation, characterized by an optimal tax system, liberal trade policies, and a stable exchange rate, are crucial factors in the attraction of top-tier domestic and foreign investors.

Moreover, environmental sustainability was also undermined by financial development in Central Africa. Financial institutions in the region are redirecting their support to the production of carbon-intensive products rather than more environmentally sustainable alternatives. It is imperative that industry stakeholders are not persuaded to prioritize the long-term advantages of endorsing environmentally sustainable practices over the immediate gains derived from backing energy-intensive enterprises. Financial institutions in the region offer credits to firms at a relatively higher interest rate compared to their Asian counterparts. There is a critical need for a thriving financial sector that offers lower interest rates. Furthermore, it is noteworthy that climate finance is in its nascent phase within the region, and therefore warrants significant consideration.

The study has several theoretical implications to help policymakers and investors to make informed decisions to harness the potential of green investments, information and communication technology, foreign direct investment, financial development, economic growth, nonrenewable energy consumption, and population growth in enhancing environmental quality in Central Africa. First, green investments and ICT can promote the transition from polluting energies like fossil fuels to renewable energy sources like wind, solar, and hydro among others, thereby decreasing greenhouse gas emissions in the region. Also, ICT and green investments can stimulate the adoption of circular economy principles, thereby reducing waste and encouraging recycling. Besides, data-driven decision-making can be made much easier through the adoption of ICT. This can allow for real-time monitoring of emissions and environmental indicators, consequently improving environmental quality in the region.

Moreover, FDI can improve production efficiency by reducing the per-unit output of emissions. FDI can also encourage green

TABLE 13 | Dumitrescu Hurlin panel causality tests results.

Assumptions	W-Stat.	Zbar-Stat.	Prob.	Findings
lnPOP ⇏ lnGHG	15.67	10.34	0.00***	One-way
lnGHG ⇏ lnPOP	0.47	−0.68	0.78	
lnGDP ⇏ lnGHG	11.48	7.22	0.00***	One-way
lnGHG ⇏ lnGDP	1.57	0.49	0.28	
lnGF ⇏ lnGHG	10.26	6.52	0.00***	One-way
lnGHG ⇏ lnGF	1.95	0.58	0.14	
lnFDI ⇏ lnGHG	9.47	6.33	0.00***	One-way
lnGHG ⇏ lnFDI	1.65	0.52	0.22	
lnNRE ⇏ lnGHG	11.24	7.18	0.00***	One-way
lnGHG ⇏ lnNRE	0.53	−0.63	0.65	
lnICT ⇏ lnGHG	13.48	9.51	0.00***	One-way
lnGHG ⇏ lnICT	1.24	0.42	0.34	
lnFD ⇏ lnGHG	10.45	6.92	0.00***	Two-way
lnGHG ⇏ lnFD	7.73	5.48	0.02**	
lnFD × lnGF ⇏ lnGHG	9.42	5.76	0.00***	Two-way
lnGHG ⇏ lnFD × lnGF	6.41	3.94	0.03**	
lnFD × lnFDI ⇏ lnGHG	14.73	9.78	0.00***	Two-way
lnGHG ⇏ lnFD × lnFDI	8.04	5.32	0.00***	
lnFD × lnNRE ⇏ lnGHG	11.85	7.62	0.00***	Two-way
lnGHG ⇏ lnFD × lnNRE	5.10	3.27	0.05*	
lnFD × lnICT ⇏ lnGHG	1.79	0.56	0.19	No causation
lnGHG ⇏ lnFD × lnICT	1.06	0.37	0.45	
$lnGF^2$ ⇏ lnGHG	12.44	8.53	0.00***	Two-way
lnGHG ⇏ $lnGF^2$	9.56	6.41	0.00***	
$lnFDI^2$ ⇏ lnGHG	10.33	6.76	0.00***	Two-way
lnGHG ⇏ $lnFDI^2$	8.34	5.54	0.00***	
$lnNRE^2$ ⇏ lnGHG	3.72	2.44	0.06*	One-way
lnGHG ⇏ $lnNRE^2$	0.56	−0.53	0.56	
$lnICT^2$ ⇏ lnGHG	12.54	8.71	0.00***	Two-way
lnGHG ⇏ $lnICT^2$	9.43	6.25	0.00***	
$lnGDP^2$ ⇏ lnGHG	11.68	7.31	0.00***	Two-way
lnGHG ⇏ $lnGDP^2$	8.45	5.67	0.00***	

Note: The triple * and the double * show significance at the 1% and 5% levels accordingly.

and efficient technologies resulting in pollution reduction and environmental quality improvement. The theoretical implications of this study also recommend improving institutional frameworks, increasing transparency and accountability, fostering linkages with the local economy, protecting strategic sectors, promoting human rights and labor standards, environmental impact assessment, and developing human capital. Diversifying investment resources, and monitoring evaluation to help mitigate the detrimental effects of FDI on the environment.

To lessen the damaging effects of nonrenewable energy on environmental quality in Central Africa, theoretical implications suggest carbon pricing and regulation, sustainable resource management, investment in green technologies, transition to green energy sources, and increased efficiency. Besides, financial development can promote green bonds, carbon credits, and other green financial instruments that could enhance environmental quality in the region. To further mitigate the damaging environmental effects of financial development in Central

Africa, the theoretical implications of this study suggest good international cooperation, effective regulatory frameworks, sustainable investment practices, green finance initiatives, and environmental risk management.

Furthermore, economic growth can be decoupled from environmental pollution via resource efficiency, green technologies, inclusive growth, green economy, social safety nets, investment in human capital, quality institutions, and sustainable consumption practices. To finally reduce the damaging environmental effect of population growth in Central Africa, the theoretical implications of this study suggest education and family planning, resource management, sustainable agriculture, urban planning, environmental conservation, effective population policies, renewable energy transition, demographic analysis, and good water and waste management systems.

5.1 | Limitations and Direction for Future Studies

Insufficient data availability posed some challenges to the extent of the scope of the current study which was restricted to the period 1996–2019, with the exclusion of a few other countries in the region including Chad and the Central African Republic. It is worth noting that some of these countries have been broadly affected by a series of political instability over the years which might have affected the functionality of some of their institutional establishment for data recording. These countries were outrightly excluded either due to a partial absence of data on some of the understudied factors or where there is a substantial long period of missing observations. Consequently, we extrapolate missing points in a few instances. For example, in 2018 a single period data point was missing for fixed telephone subscriptions (per 100 people) in the Republic of Congo observation. Thus, overall, the extent of the analysis was restricted to the 5 countries in the region. Hence, researchers can leverage the framework of the current study to expand the scope of future works. Additionally, future research can also provide country-level analysis to carter for any potential effect of country-specific characteristics/differences in analyzing the emission-mitigating roles of green investment while integrating the moderating influences of other factors.

Data Availability Statement

The data for this present study are sourced from the database of the World Bank's World Development Indicators (https://data.worldbank.org).

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