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Exploring the influence of green growth and energy sources on "carbon-dioxide emissions": implications for climate change mitigation

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Climate change is a global concern driven by greenhouse gas emissions. Bangladesh, being densely populated and a significant carbon emitter, must urgently reduce its "carbon-dioxide emissions". The primary objectives of this research are to meticulously examine the impact of green growth, non-renewable energy, renewable energy, and technological innovations on carbon dioxide emissions in Bangladesh from 1990 to 2020, with the goal of informing policies for effective and sustainable climate change mitigation in Bangladesh. The analysis using advanced econometric methods, including autoregressive distributed lag, fully modified ordinary least squares, and canonical cointegration regression, reveals that green growth and technological innovations have adverse long-term but positive short-term effects on carbon emissions in Bangladesh. Additionally, it is noteworthy that both non-renewable and renewable energy sources significantly contribute to long-term and short-term carbon emissions. The study confirms the Environmental Kuznets Curve, showing a "∩" shaped relationship between green development and carbon emissions. Policymakers should prioritize green growth, incentivize technological innovation, promote sustainable economic practices, and implement comprehensive energy transition strategies. The insights from this study inform policy formulation to address the complex relationships between green growth, energy sources, and carbon-dioxide emissions for sustainable climate change mitigation in Bangladesh. Bangladesh's efforts contribute to global emission reduction and foster a resilient future.

KEYWORDS

climate change, green growth, carbon-dioxide emissions, technological innovation, Bangladesh

1 Introduction

In the modern era, climate change poses a continuous threat to the global environment. Scientific evidence suggests that climate change directly and indirectly affects humanity (Read, 2004; Institute of Medicine, 2011; Froese and Schilling, 2019). It leads to increased pollution, global warming, summer deaths, rising sea levels, extreme droughts, floods, forest fires, abnormal rainfall, and tropical cyclones (Patz et al., 2014; Global Change, 2018; Akhtar, 2019; Gulzar et al., 2021). The decline in crop production and the melting of glaciers and polar ice regions can be attributed to global climate change (Ashrafuzzaman and Furini, 2019), highlighting its destructive impact on ecosystems and the environment.

Bangladesh, a densely populated South Asian nation, faces significant challenges in "carbon-dioxide emissions" (CDOE), energy sources, technological innovation, and sustainable growth (Raihan et al., 2022a). As a developing country, it must balance increasing energy demands with environmental concerns for sustainable development. Geographically vulnerable, Bangladesh's delta region experiences natural disasters due to factors like illiteracy, flat landscape, and periodic flooding (Uddin et al., 2019).Its unique physical and social conditions distinguish it from other vulnerable nations (Sen et al., 2004), with 80% of land as floodplains during the rainy season. Climate change primarily stems from increased greenhouse gas (GHG) emissions from human activities, deforestation, and fossil fuel combustion (Mackay, 2008; Parry et al., 2007). CDOE is particularly influential. Escalating global temperatures due to these emissions leads to record-breaking annual climate changes (IPCC, 2013). predicts a median temperature rise of 1.4°C–5.8°C by 2100, with higher increases on land.

Consequently, global average rainfall is expected to increase, while many middle-latitude and coastal regions may become drier. Coastal areas will face more frequent and intense precipitation events, threatening valuable agrarian land. The "United Nations Framework Convention on Climate Change" (UNFCCC) has set instructions to stabilize GHG levels of presence in the atmosphere that do not pose a threat (Pulselli and Marchi, 2015). Research suggests that increasing economic activities contribute to higher pollution levels (Álvarez-Herránz et al., 2017), and CDOE is strongly correlated with rapid economic growth (Yavuz, 2014; Al-Mulali and Che Sab, 2018). However, adopting energy-efficient technologies and renewable energy sources can curb emissions and drive green growth (Joo et al., 2015).

Since the 1990s, Bangladesh has been confronting a substantial issue-precisely, the challenge of CDOE. This issue primarily results from its significant reliance on fossil fuels for energy transportation and production. The rapid industrialization and urbanization in the country have resulted in a substantial surge in CDOE, leading to environmental degradation and heightened vulnerabilities to climate change. Recognizing the urgency of the situation, Bangladesh has proactively undertaken endeavors to diminish its environmental footprint and shift towards low-carbon development (Sarker, 2017; Karim et al., 2019; Roy et al., 2021). However, global energy demand continues to rise, presenting a major challenge. According to research, emissions from developing countries are projected to exceed those from OECD countries by a significant 72% by 2030 (Cofala et al., 2007; Bierbaum and Zoellick, 2009; Hatfield-Dodds et al., 2017).

Bangladesh has implemented various initiatives and policies to promote the adoption of sustainable energy sources and improve energy efficiency in order to foster environmentally-friendly economic growth. The government has emphasized harnessing solar and wind energy, as well as integrating hydroelectric power, to broaden the energy portfolio and reduce dependence on fossil fuels (Rofiqul Islam et al., 2008; Abdulrazak et al., 2021a; Mohazzem Hossain et al., 2023). Additionally, energy-saving technologies and practices have been promoted to optimize energy consumption across different sectors, contributing to alternative energy generation and steady green growth (Wang et al., 2018). The expansion of renewable energy is perceived as a trustworthy pathway to alleviate environmental pressures and establish a safe, sustainable, and independent energy system worldwide (Omer, 2008; Dincer and Rosen, 2020).

Technological innovation plays a crucial role in Bangladesh's efforts to address these challenges. The country has invested in research and development (RnD) to develop sustainable and eco-friendly technologies, particularly in the realms of renewable energy, agriculture, and infrastructure (Islam et al., 2013). Collaborations with international organizations and other countries have facilitated access to technological expertise and resources, accelerating Bangladesh's progress towards its sustainable development goals. While Bangladesh faces significant hurdles in reducing CDOE, promoting green growth, and embracing technological innovation, its commitment and proactive measures demonstrate its determination to tackle these complex issues (Huda, 2023). Bangladesh aspires to achieve a future that is both environmentally sustainable and robust, by harmonizing green economic growth with adequate environmental safeguards through the adoption of renewable energy, energy-efficient practices, and innovative solutions (Abdulrazak et al., 2021b; Vargas-Hernández and Ali, 2023; Qing et al., 2024).

We chose Bangladesh for this research because of its significant vulnerability to climate change and the ongoing need to develop effective strategies for managing CDOE amidst rapid economic growth. This study encounters several challenges, including difficulties in obtaining reliable data on CDOE and green growth initiatives. Integrating strategies aimed at reducing emissions and promoting sustainable practices into existing economic frameworks could be complex. A limited public understanding and awareness of these initiatives may diminish their effectiveness. Furthermore, evaluating the long-term outcomes of efforts to lower emissions and enhance sustainability in a rapidly changing environment may prove to be quite challenging.

This study aims to provide an in-depth analysis of the complex linkages between Bangladesh's economic activities, energy sources, climate vulnerabilities, and green growth initiatives. Examining these interconnections can inform policies and strategies to foster a low-carbon, climate-resilient future for Bangladesh, bridging the research gap on the CDOE-energy-climate-green growth nexus. The main objective of this study is to focus on the relationship between CDOE, energy sources, climate change, and green growth, analyzing the changes in Bangladesh's energy sources over time and its implications for GHGs, and exploring the policy and technological interventions that could promote green growth and a low-carbon transition in Bangladesh. While existing research on CDOE and green growth exists globally, localized studies considering Bangladesh's unique socio-economic and environmental factors are greatly needed. This research assesses Bangladesh's current CDOE profile, identifies barriers and opportunities for green growth, evaluates the feasibility and effectiveness of different renewable energy options, and analyzes the potential of technological innovations within the Bangladeshi context. By examining these aspects, policymakers, researchers, and stakeholders can acquire valuable perspectives on the challenges and explore viable solutions for promoting green growth and addressing climate change in Bangladesh.

The Auto-Regressive Distributed Lag F-Bound Test (ARDLF-BT) has gained significant traction in scholarly investigations, serving as a valuable tool to scrutinize the causal connection among (CDOE, economic growth, and various factors in diverse countries (Narayan and Narayan, 2010; Al-Mulali et al., 2016; Polome and Trotignon, 2016; Etukafia et al., 2017; Le and Ozturk, 2020; Sulub et al., 2020; Anser et al., 2021; Dahmani et al., 2021; Pata and Isik, 2021; Vikia et al., 2023) and the Environmental Kuznets Curve (EKC), highlighted by (Grossman and Krueger, 1991) links green growth to environmental degradation, initially positive but later negative as income levels increase (Narayan and Narayan, 2010; Al-Mulali et al., 2016; Gökmenoğlu and Taspinar, 2016; Jahanger et al., 2022). In this study, the ARDLF-BT model (Pesaran and Shin, 1999; 2012; Narayan and Smyth, 2005; Pesaran, 2008; Sultanuzzaman et al., 2018) is utilized to investigate the long-term equilibrium association of climate change, green growth, energy sources, and energy-efficient technology from 1990 to 2020. The ARDLF-BT model effectively addresses endogeneity by incorporating lagged values of the dependent and explanatory variables, accommodating potential bidirectional relationships between CDOE and the explanatory variables. Additionally, it can handle a combination of stationary variables, allowing for the analysis of mixed orders of integration (without 2nd difference) (Narayan and Narayan, 2010; Reza et al., 2018; Sultanuzzaman et al., 2018). By incorporating lagged values, the ARDL model captures both short-run and long-run dynamics between the variables, enabling a comprehensive analysis of the relationship over different time horizons. The ARDLF-BT model facilitates the selection of an optimal lag length and model specification using information criteria like the Akaike Information Criterion (AIC) and Schwarz Information Criterion (SIC), ensuring a parsimonious and statistically sound representation of the relationship between the variables (Bork, 2011; Shahbaz et al., 2018). Moreover, it can detect cointegration, indicating a stable long-term relationship where the variables move together. Identifying cointegration enables a more comprehensive exploration of the equilibrium relationship between CDOE and the explanatory variables (Ahmad and Du, 2017; Hussain and Dogan, 2021). detects cointegration, indicating a stable long-term relationship between variables.

To ensure the reliability of the ARDLF-BT model's results, this study employs the Fully Modified Ordinary Least Squares (FMOLS) (Phillips and Hansen, 1990) and Canonical Cointegration Regression (CCR) (Park, 1992) as robustness checks. FMOLS addresses endogeneity and serial correlation by incorporating a correction term into the Ordinary Least Squares (OLS) estimator, enabling reliable and effective estimation of long-run parameters (Zimon et al., 2023). Conversely, CCR employs an iterative process to obtain long-term estimates in the presence of heteroscedasticity (Balcombe and Davis, 1996). By addressing econometric issues, FMOLS and CCR analysis provide additional support for the validity and reliability of the ARDL model's findings (Ahmad and Du, 2017; Doğan, 2019; Camba, 2020; Nathaniel and Bekun, 2021; Chu and Le, 2022; Zimon et al., 2023). Additionally, the study applies the VAR Granger causality test (Zeb et al., 2014; Yii and Geetha, 2017; Raihan et al., 2022b) to ascertain the directional association between climate change (CDOE), green growth, energy sources, and technological advancements in Bangladesh. Furthermore, a key aspect of the study is the forecast of CDOE in Bangladesh from 1990 to 2030 using the VAR-impulse response function (IRF) model (Magazzino, 2014; Christensen et al., 2021; Wang et al., 2022). By employing the IRF forecasting technique, the researchers aim to provide insights into the potential trajectory of CDOE and their implications for green growth in the country. This predictive analysis can help policymakers and individuals involved in decision-making gain insights into upcoming patterns and develop sustainable approaches for promoting long-term, environmentally-friendly progress. Also, this study provides significant insights into Bangladesh's CDOE dynamics. By bridging the gap between empirical literature and practical implications for climate change mitigation, this research underscores the importance of investing in renewable energy solutions while highlighting the need for immediate policy interventions to manage emissions effectively.

Furthermore, the study presents a unique perspective on CDOE and green growth in Bangladesh through a robust analytical framework that integrates FMOLS and CCR as additional tests alongside the ARDLF-BT model, emphasizing climate change mitigation. It provides nuanced insights into both short- and long-term impacts. Unlike other studies, it highlights the dual role of renewable and non-renewable energy in influencing emissions, emphasizing the urgent need for targeted policy interventions. The study's novelty lies in this innovative combination, which not only strengthens the findings but also enables a more comprehensive exploration of the long-term relationships among CDOE, green growth, and energy sources. The results reveal complex interactions, suggesting that while renewable energy generally aids in reducing emissions when comparing both short- and long-term effects, non-renewable sources can unexpectedly lead to higher CDOE levels. Focusing on green growth and technology as long-term solutions offers new insights into sustainable development strategies. Additionally, the application of IRF to forecast CDOE from 2021 to 2030 introduces a predictive element that is often lacking in similar studies in Bangladesh, further enhancing the study's originality and its contributions to the fields of environmental economics and climate policy. This unique methodological approach and exploring new dimensions in CDOE dynamics distinctly position this research within the existing literature. This study contributes to the discussion on climate change mitigation in Bangladesh by advocating for balanced strategies considering the benefits and drawbacks of different energy sources as well.

The research report is organized into several parts. The second part consists of a comprehensive literature review. Subsequently, in part three, the data collection process is described, including the data sources, variables considered, and the research methodology employed, which encompasses research design, variable selection, and data analysis techniques. This section also provides a rationale for the chosen methodology, justifying its suitability for addressing the research objectives. Part 4 focuses on research findings and discussion, presenting them logically and coherently. The implications of the findings concerning the existing literature are interpreted and discussed, supported by tables and graphs for enhanced clarity. The conclusion summarizes the main findings, restates the research objectives, discusses implications and potential contributions, explores policy implications, identifies potential actions, and provides a rationale for the proposed policy recommendations.

2 Related literature

Bangladesh is encountering an increase in CDOE as a result of swift industrialization and urban expansion. To reconcile economic progress with environmental responsibility, the country must adopt sustainable energy solutions. Green growth focuses on efficient resource use, pollution reduction, and ecosystem preservation, aligning with Bangladesh's Nationally Determined Contributions (NDCs) under the Paris Agreement, which aim to reduce emissions while promoting development (Khan et al., 2021; UNFCCC, 2023). Effective resource management is essential for minimizing waste and emissions. Sustainable land management practices can increase productivity and diminish GHGs (Rahman et al., 2020). Drawing from the theoretical standpoint, the literature extensively examines the economic ramifications of the climate crisis, a compelling concern in the contemporary epoch. Numerous global and regional studies have been conducted to assess these consequences, providing valuable insights. Researchers (Agras and Chapman, 1999; Richmond et al., 2007; Omer, 2008; Streimikiene and Šivickas, 2008; de Lucena et al., 2009; Ozturk and Acaravci, 2010; Shanthini, 2012; Yavuz, 2014; Zeb et al., 2014; Al-Mulali et al., 2016; Karim et al., 2020; Khan et al., 2020; Lee et al., 2023; Liu et al., 2023) have contributed to the comprehending of the economic implications of climate change. Thus, the EKC hypothesis posits that economic growth initially worsens environmental conditions before improving at higher income levels (Kuznets, 1955; Grossman and Krueger, 1995; Meo et al., 2023). In Bangladesh, transitioning to renewable energy is essential for decoupling growth from CDOE and promoting sustainability. According to this framework, prioritizing green technologies enhances climate resilience and economic development. Effective policy changes, including renewable energy incentives and sustainable infrastructure investments, are crucial for this transition.

Moreover, integrating green technologies in construction and transportation improves resource efficiency. Transitioning to low-carbon technologies is crucial, and Bangladesh has made strides through its Solar Home Systems (SHS) initiative, which has installed millions of solar units in rural areas, reducing dependence on fossil fuels and enhancing energy access (Al-tabatabaie et al., 2022). Protecting vital ecosystems is also key to mitigating climate change, as these areas play a significant role in carbon sequestration and coastal defense (Pandey and Ghosh, 2023). However, the energy sector's heavy reliance on fossil fuels, particularly coal, presents sustainability challenges (Mohazzem Hossain et al., 2024). It is critical to diversify energy sources and increase renewable energy generation to 10% by 2020 (Murshed et al., 2021; Al-tabatabaie et al., 2022).

Strong governance and effective policies are essential for promoting green growth. Enforcing environmental regulations and offering financial incentives, such as tax breaks for renewable energy projects, can stimulate innovation (Sarker et al., 2023). Raising awareness about climate change and encouraging sustainable practices can foster community engagement (Anthony, 2024). Aligning national policies with international climate commitments is vital for Bangladesh's sustainable development. The country's comprehensive NDCs demonstrate its commitment to addressing climate change while pursuing economic growth (UNFCCC, 2023). While economic growth increases the ecological footprint, utilizing more renewable energy can help decrease it (Zhang et al., 2024). Enhancing energy efficiency and increasing renewable energy sources can reduce CDOE, while economic growth tends to raise them. A regulatory framework aimed at improving energy efficiency, supporting renewable energy, and promoting sustainable urban development is essential for achieving net-zero emissions and assisting other countries in adopting cleaner energy (Anser et al., 2024). The ARDLF-BT method examines data from 1990 to 2015 in nine developing countries, revealing that energy consumption and economic growth elevate CDOE, while rural population growth has no effect. Adopting renewable sources such as hydro and biofuels can lower CDOE (Shaari et al., 2021).

Technology plays a crucial role in supporting environmentally sustainable growth by enhancing industrial efficiency through renewable energy, establishing new green sectors such as clean energy, and facilitating innovations that lead to the creation of new industries. Over time, it is vital to shift from fossil fuels to renewable energy sources like solar, wind, and hydro power (Fatima et al., 2021; Shaari et al., 2021). This approach can foster a supportive environment for renewable energy use in Bangladesh, aiding the country in achieving its climate goals and enhancing energy security.

2.1 CDOE, non-renewable energy and economic growth

Researchers observe the relationship between environmental outcomes and economic growth in different countries, highlighting the necessity of implementing effective policies for sustainable growth (Awosusi et al., 2022). focus on this relationship in Uruguay from 1980 to 2018, finding a positive correlation between GDP, non-renewable energy, and CDOE through ARDL analysis.

Meanwhile, S. R. Lee & Yoo, (2016) implicate Korea from 1971 to 2008 and find a unidirectional causality from CDOE to economic growth, as well as bidirectional associations between energy consumption and economic growth. In Greece (Hondroyiannis et al., 2002), identify a meaningful bidirectional connection between energy consumption and GDP growth, whereas (Dergiades et al., 2013) discovered a noteworthy unidirectional link from aggregated energy to economic growth from 1960 to 2008.

Furthermore, Bekhet et al. (2017) explore the relationships among CDOE, energy consumption, economic growth, and financial development in GCC countries using the ARDLF-BT and Granger causality. The study identifies a long-term equilibrium connection, except in the UAE, and diverse causality patterns between these variables (Tancho et al., 2020). demonstrate a significant positive correlation between economic growth and CDOE in Thailand from 1990 to 2018, highlighting how industrial development boosts production and subsequently increases CDOE. In contrast, a panel ARDL analysis of the EU from 1990 to 2021 shows a negative relationship between GDP and CDOE (Voumik). A similar analysis of Brazilian states from 1997 to 2016 reveals comparable findings (Amarante et al., 2021). Furthermore, research in Pakistan from 1990 to 2020 (Lin and Ullah, 2024) employs advanced dynamic ARDLF-BT approaches and demonstrates a negative influence of growth on CDOE.

Recently, this introspection concerns NAFTA countries from 1990 to 2018, finding a "∩" shaped (EKC) relationship between economic growth and CDOE, encountering that boosted natural resource consumption leads to higher emissions, and increased renewable energy lowers emissions in the long run (Jahanger et al., 2022). Yavuz's study reveals a significant association between CDOE, energy consumption, and income *per capita*. The study validates the EKC, indicating a "∩" shaped curve between economic development and environmental degradation. With the rise in *per capita* income, there was an initial increase in CDOE, followed by a subsequent decline. This pattern implies a transition towards cleaner technologies in conjunction with economic growth (Yavuz, 2014). Other findings support a "∩" shape hypothesis and propose a phased policy framework for transitioning to green energy, starting with households and later targeting the industrial sector (Xie et al., 2022). Likewise, Joo et al. (2015) dissect the interconnection between CDOE, energy consumption, and economic growth in Chile from 1965 to 2010. The results initiate a unidirectional association, with CDOE influencing economic growth. Additionally, energy consumption positively persuades both economic growth and CDOE. Ang, (2007) dissects the correlation between CDOE, GDP growth, and energy consumption in France from 1960 to 2000. The study builds a significant association between CDOE, energy consumption, and GDP growth, indicating a bidirectional influence among these variables.

On the contrary, Hasanov et al. (2019) scan the causal interrelations between CDOE and economic growth in Kazakhstan from 1992 to 2013. The "∩" shaped curve did not clasp in the long run, but the country's growth was monotonically increasing, suggesting policymakers should focus on using more renewable energy to reduce higher pollution in Kazakhstan. A study in Ghana using the ARDLF-BT approach finds a U-shaped relationship between CDOE and industrial growth, contradicting the EKC hypothesis. It emphasizes the significant influence of financial development and fossil fuel consumption on CDOE, advocating for better energy efficiency and greater renewable energy adoption (Abokyi et al., 2019). Other research supports that fossil fuel consumption contributes to CDOE and suggests promoting green innovation during economic upturns and addressing funding gaps to address environmental challenges (Ahmad and Zheng, 2021). M. K. Khan et al. (2019) employ a dynamic ARDL model to appraise the ramifications of oil, gas, and coal consumption, along with economic growth, on ecological degradation in Pakistan. The findings demonstrate that oil, gas, and coal consumption positively influenced both short- and long-term ecological degradation. However (Zhou et al., 2023), uncover that economic growth and reliance on non-renewable energy sources lead to higher CDOE, while other factors help lower emissions in different nations between 1990 and 2020. The results highlight the importance of renewable energy and stronger environmental policies for promoting sustainability.

Similarly (Ibrahim et al., 2023), uncover positive connections between CDOE and nonrenewable energy in BRICS from 1992 to 2019. Shifting to renewable energy can mitigate fossil fuel harm, requiring investment from both public and private entities. Meo et al. (2023) demonstrate that the use of non-renewable energy and economic expansion result in greater CDOE. They advocate for developing a long-term investment framework for renewable energy in Pakistan. A study of Vietnam from 1984 to 2019, utilizing dynamic ARDL and spectral Granger-causality tests, reveals that CDOE rises with nonrenewable energy consumption and economic growth, while renewable energy reduces CDOE. Vietnam should implement carbon reduction strategies that support economic growth, prioritizing energy-efficient renewable technologies (Awosusi et al., 2023).

2.2 CDOE, renewable energy and technology

Advancements in renewable energy technologies are essential for lowering CDOE and require supportive policies and investments for effective implementation. Precisely, a study appraises CDOE, economic growth, and renewable energy in Germany (1975–2014) using ARDL and VAR. The study identifies a long-term relationship but asserts that greater reliance on renewables provides no environmental benefits. This shift may also increase costs for producers and hinder nations' growth (Khoshnevis Yazdi and Shakouri, 2018). This study assesses the impact of green technology on CO_2 emissions in 45 countries from 1989 to 2018. It determines that renewable energy lowers emissions in high and middle-income nations, while lower-middle-income countries experience positive effects. The results highlight the need for developing countries to foster green innovation for carbon neutrality (Milindi and Inglesi-Lotz, 2022). Likewise, another research reveals that positive correlations exist between renewable energy and CDOE in India (1990q1-2018q4), as rising energy demand may lead to increased fossil fuel use and a declining share of renewable energy (Shabbir Alam et al., 2023). Tiwari et al. (2015) verify the cointegration relationships among renewable energy, GDP growth, and non-renewable energy in 12 sub-Saharan African (SSA) nations from 1971 to 2011. The findings reveal a long-term positive linkage among these variables in SSA nations. Also, a panel ARDL report studies the impact of renewable and non-renewable energy on sustainable development in select Asian economies (1990–2020), revealing that renewable energy, GDP, and foreign direct investment improve sustainability, while non-renewable energy has a negative effect. The report urges the promotion of renewable energy, investment in research, implementation of environmental taxes, and alignment with SDG 7 (Wei and Huang, 2022).

Another research evaluates the role of green technology and renewable energy in CDOE and GDP growth in Malaysia, utilizing the Bootstrap ARDLF-BT approach from 1971 to 2017. The findings demonstrate that green technology positively impacts GDP growth and reduces CDOE, while renewable energy negatively correlates with CDOE in the short and long run. These results emphasize the need for policies promoting environmental protection, green advancements, and the effective utilization of renewable energy for sustainable development (Suki et al., 2022). A study of 24 OECD countries divulges that green innovation and economic growth increase CDOE, while renewable energy and social inclusivity decrease emissions. This emphasizes the importance of investing in green energy, promoting social inclusion, and implementing policies supporting education, job creation, and climate resilience in underserved communities to reduce CDOE and foster economic growth (Shobande et al., 2023). However, this research scans the association between environmental pollution, financial development, and renewable energy consumption in ASEAN+3 nations from 1998 to 2018 using panel ARDL and the Dumitrescu-Hurlin causality test. The findings divulge that financial development hampers renewable energy adoption, while there is an inverse connection between environmental pollution and renewable energy consumption. Innovations and economic growth promote the consumption of renewable energy, but economic freedom hinders it. Policymakers should support the energy sector financially, implement pollution-reducing policies, and collaborate with neighboring countries for knowledge sharing and investment in sustainable projects (Assi et al., 2021). Contrary to expectations, there are cases where economic growth has little impact on ecological degradation. For instance, a study on North African countries suggests that increasing renewable energy use could stimulate output growth while reducing CDOE and dependence on fossil energy (Ben Jebli and Ben Youssef, 2015).

In recent years, this paper scrutinizes the influence of technological innovation and renewable energy on CDOE in China from 1985 to 2019. The ARDL results exhibit that GDP and structural change contribute to higher CDOE, while renewable energy use and technological innovation reduce emissions (Xie et al., 2022). Hussain & Dogan, (2021) establish a substantial and positive correlation between CDOE, GDP, and energy consumption in their study in Pakistan 1992–2016, both in the long and short run. Technology exhibits a negative association with CDOE. The Granger causality findings conjecture a significant bidirectional connection between CDOE and energy consumption. Similarly, Joo et al. (2015) state that Chile prioritizes renewable electricity sources and increases green technology-based energy production to decrease CDOE and achieve sustainable green growth. Findings on China's provinces indicate strong positive correlations between pollution emissions and regional disparities in green technology innovations. Some innovations yield positive spillover effects on pollution reduction, but their overall impact is insufficient. Targeted regional control plans are necessary to enhance the spread of green technologies for effective pollution mitigation (Kuang et al., 2022). Another report explores the cyclical effects of IERT (Innovations in environmental-related technologies) on CDOE within BRICS economies spanning from 1990 to 2016. The panel ARDL approach confirms long-term connections between the variables, with solid outcomes generated via FMOLS and DOLS methodologies. Positive IERT shifts decrease CDOE, while negative shifts increase them (Ahmad and Zheng, 2021). Another panel ARDL analysis in the European Union from 1991 to 2021 reveals significant impacts of GDP, renewable and nuclear energy, energy intensity, and R&D on CDOE. The study challenges the EKC hypothesis and underscores the need for more robust green technology initiatives and increased investment in renewable and nuclear energy (Voumik et al., 2022).

2.3 The rationale of the research

This study responds to the urgent need for effective climate change mitigation strategies in Bangladesh, a country significantly impacted by climate challenges. As policymakers confront rising emissions, it is vital to explore the specific factors influencing CDOE. Although earlier studies have tackled this issue from multiple angles (Hasan and Chongbo, 2020; Hasan et al., 2022; Raihan et al., 2022a), this research concentrates on specific explanatory variables to provide more precise insights. By employing advanced econometric techniques, it aims to provide evidence to inform targeted emissions reduction strategies. Additionally, the research emphasizes stakeholder engagement and adaptive policy frameworks to enhance the effectiveness of climate initiatives and ensure long-term resilience.

2.4 Research gap

The existing literature enlightens that few studies have explored the link between CDOE, energy sources, technology, and green growth across different countries and regions. The impact of these factors remains a subject of active discussion. Some studies endorse a "∩" shaped (EKC) connection between income and environmental deterioration, while others reveal different trends influenced by factors such as data selection, methodologies, and specific variables. This study intends to address these discrepancies by identifying the causes behind varying results, examining specific factors influencing emissions, and assessing the impact of cleaner energy and renewable sources. It will also analyze the effectiveness of eco-friendly policies in promoting sustainability, reducing CDOE, and encouraging renewable energy use. Additionally, the research will investigate how technology can aid in reducing emissions, evaluate green growth strategies, and compare findings across different regions in Bangladesh. Ultimately, it aims to clarify the link between economic development and environmental sustainability, promoting integrated policy solutions to address climate challenges.

3 Materials and methods

The ARDLF-BT model is an econometric approach deployed to assess the sustained linkage between variables with different integration orders academicians (Pesaran and Shin, 1999; 2012; Narayan and Smyth, 2005; Pesaran, 2008; Ahmad and Du, 2017;

TABLE 1 Variable descriptions.

Variable	Explanation	Collected source
CDOE	This metric measures a country's total carbon dioxide emissions divided by its population, expressed in kilotons (Esso and Keho, 2016; Sultana et al., 2023). It represents the average CDOE per person, with higher values reflecting a greater dependence on fossil fuels and industrial activities, thereby underscoring a nation's impact on climate change	World Bank
GGR	Adjusted net savings measures a country's savings rate by accounting for the depreciation of natural capital and the costs of environmental degradation, including particulate emission damage. Expressed as a percentage of Gross National Income (GNI), it serves as a proxy for green growth, indicating the sustainability of economic development (Wei and Huang, 2022). This metric helps evaluate the effectiveness of climate change mitigation policies by ensuring that economic growth does not undermine environmental integrity	World Bank
NRE	Non-renewable energy comes from finite fossil fuels like coal, oil, and natural gas, measured in million tonnes of oil equivalent (toe) (Joo et al., 2015; Tiwari et al., 2015). It reflects a country's dependence on these resources and contributes to GHG emissions, highlighting the need for a shift to renewable energy to mitigate climate change	OECD Database
RE	Renewable energy conveys the portion of energy generated from sustainable sources such as solar, wind, hydro, and biomass, quantified as a percentage of a country's total energy supply (Tiwari et al., 2015; Sultana et al., 2023). This clean energy reduces GHG emissions and plays a crucial role in climate change mitigation by decreasing reliance on fossil fuels and promoting environmental sustainability	OECD database
TEC	Technological innovation involves creating and implementing improved technologies to enhance efficiency and competitiveness. It is measured by the number of patents, reflecting a country's research and development capacity (Dinda, 2018; Li et al., 2021).This innovation is essential for addressing climate change, as it promotes solutions such as renewable energy and energy efficiency, reducing GHG emissions and fostering sustainability	World Bank

Etukafia et al., 2017; Sultanuzzaman et al., 2018; Khan et al., 2019; Assi et al., 2021; Pata and Isik, 2021; Darsono et al., 2022; Zimon et al., 2023). Furthermore, this study articulates its methodology, drawing motivation from the works of Chandio et al. (2020), Zimon et al. (2023), Pattak et al. (2023), and Lin and Ullah (2024) concerning climate change mitigation. In addition, these studies offer valuable insights into practical environmental solutions. The data employed in this study covers the period from 1990 to 2020 and is acquired from the World Bank (https://data.worldbank.org) and OECD (https://www.oecd.org/en/data.html) repositories. The model incorporates error correction (EC) and assumes deviations from long-run equilibrium are corrected in the next period. Ordinary least squares (OLS) or maximum likelihood estimation (MLE) is employed to estimate the model, and appropriate lag lengths are specified. Cointegration is tested using methods such as the F-bound test. After establishing cointegration, the estimator can quantify long-run coefficients and scrutinize short-run dynamics using the error correction model (ECM). The ARDLFBT model is favoured for its flexibility, simplicity, and ability to capture both short and long-term effects (Pesaran and Shin, 1999; 2012; Narayan and Narayan, 2010; Etukafia et al., 2017; Shahbaz et al., 2018; Khan et al., 2019; Darsono et al., 2022). To ensure reliable results, it is important to carefully consider variable stationarity, specify appropriate lag lengths, and conduct various sensitivity tests. Table 1 yields descriptions of the variables, including CDOE, GGR, NRE, RE, and TEC. The data for these variables has been transformed into natural logarithm form to ensure a normal distribution in the series.

Consistent with the theoretical and experimental literature, the research generates a useful form of method to point out the consequence of CDOE on green growth. Thus, the functional shape of the model has structured in the following (Narayan and Smyth, 2005; Etukafia et al., 2017; Darsono et al., 2022):

$$CDOE = f\,(GGR, NRE, RE, TEC) \tag{1}$$

To express Equation 1 in log-linear transformation form, we can use Equation 2:

$$LNCDOE_t = \alpha_0 + \beta_1 LNGGR_t + \beta_2 LNNRE_t + \beta_3 LNRE_t + \beta_4 LNTEC_t + \varepsilon_t \tag{2}$$

In Equation 2, LN symbolizes the natural logarithm, α0 is the intercept parameter, and β1, β2, β3, and β4 correspond to the constants of the independent variables. Besides, t corresponds to the time from 1990 to 2020; ε is the error term representing white noise.

Before applying the empirical technique, the study analyzes and discusses descriptive statistics (Halicioglu, 2009; Shahbaz et al., 2013; Javaid et al., 2022), illustrated in Table 2. According to the estimation, LNNRE has the lowest mean (2.7182), while LNCDOE has the highest mean (10.4105). The standard deviation is lowest for LNRE (0.3482) and highest for LNCDOE (0.6975). These statistics provide insights into the direction, variability, skewness, kurtosis, and normality of each variable in the analysis. Preliminary evidence suggests that green growth may vary with environmental degradation.

To check the ARDL bound cointegration relationship, which is useful for dealing with a mix of integrated (I (1)) and stationary (I (0)) variables (Pesaran, 2008; Narayan and Narayan, 2010; Pesaran and Shin, 2012), the study employs the Augmented Dickey-Fuller (ADF) (Dickey and Fuller, 1979) and Phillips-Perron (PP) (Phillips and Perron, 1988) methods. The stationarity of the variables is assessed using Equation 3:

$$\Delta Z_t = \theta + \gamma_t + \sigma Z_{t-1} + u_t \tag{3}$$

Equation 3 Δ corresponds to the 1st difference; Z is a series, θ represents the constant, and u represents the error correction term. The estimators γ and σ are used, and t represents the period. Suppose the probability value from the unit root tests is less than a 5% significant level. In that case, it indicates that the series exhibits no

TABLE 2 Descriptive analysis.

	LNCDOE	LNGGR	LNNRE	LNRE	LNTEC
Mean	10.4105	2.9623	2.7182	3.5061	5.5525
Median	10.3955	3.0908	2.6947	3.5830	5.7137
Maximum	11.4715	3.4685	3.6072	4.0128	6.0234
Minimum	9.2901	2.2581	1.7261	2.8876	4.6728
Standard. Deviation	0.6975	0.3770	0.5902	0.3482	0.4025
Skewness	−0.0326	−0.5588	−0.0558	−0.3491	−1.1113
Kurtosis	1.7401	1.9094	1.8300	1.9751	2.8873
Jarque-Bera	2.0560	3.1495	1.7843	1.9865	6.3969
Probability	0.3577	0.2071	0.4098	0.3704	0.0408
Observations	31	31	31	31	31

unit root, allowing the rejection of the null hypothesis. Differencing procedures such as Δ can be applied to make the series stationary.

The study utilizes the ARDLF-BT procedure, as suggested by Pesaran and Shin in 1999, to establish the dynamic linkage between the variables. This procedure enables the incorporation of variables with varying orders of integration (I (0) and I (1)) in the same framework without the need to consider I (2) variables (Pesaran and Shin, 1999; Narayan and Smyth, 2005; Narayan and Narayan, 2010) and spurious results can arise if this criterion is not maintained (Ghouse et al., 2018). The optimal lag length, a crucial criterion for the ARDLF-BT procedure, is checked using the approach proposed by (Pesaran and Shin, 1999). The estimated ARDL model, structured according to Equation 2, is presented in Equation 4:

$$\begin{aligned}\Delta LNCDOE_t = \beta_0 + \sum_{i=1}^{p}\beta_5 \Delta LNCDOE_{t-i} \\ + \sum_{i=1}^{p}\beta_6 \Delta LNGGR_{t-i} + \sum_{i1}^{p}\beta_7 \Delta LNNRE_{t-i} \\ + \sum_{i=1}^{p}\beta_8 \Delta LNRE_{t-i} + \sum_{i=1}^{p}\beta_9 \Delta LNTEC_{t-i} \\ + \varphi_1 LNCDOE_{t-1} + \varphi_2 LNGGR_{t-1} \\ + \varphi_3 LNNRE_{t-1} + \varphi_4 LNRE_{t-1} \\ + \varphi_5 LNTEC_{t-1} + \gamma ECM_{t-1} + \varepsilon_t \end{aligned} \quad (4)$$

In Equation 4, β_0 is the intercept parameter, β_5, β_6, β_7 & β_8 are the short-run elasticities, φ_1, $\varphi_2, \varphi_3, \varphi_4$& φ_5 are the long-term elasticities, ECM_{t-1} represents the error correction metrics and γ provides the ECM coefficient indicating the rate of modification into long-term stability yearly. The null hypothesis is that $\beta_5 = \beta_6 = \beta_7 = \beta_8 = \beta_9 = 0$, while the alternative hypothesis is that $\beta_5 \neq \beta_6 \neq \beta_7 \neq \beta_8 \neq \beta_9 \neq 0$, implying the short-term association between the variables. Similarly, the null hypothesis is that $\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = \varphi_5 = 0$, and the alternative hypothesis is that $\varphi_1 \neq \varphi_2 \neq \varphi_3 \neq \varphi_4 \neq \varphi_5 \neq 0$, indicating the long-term associations of the variables.

The research applies the ARDLF-BT by (Pesaran et al., 2001) to determine the long-term cointegration relationship between variables. The formed F values are associated with Narayan's critical statistics (Narayan and Smyth, 2005). If the F-values predict cointegration among the variables in the long term, the study will run the ARDL model for both terms. Based on the estimated model, the study finds that GGR, NRE, RE, and TEC have both short and long-term effects on LNCDOE. The short-term elasticities indicate the immediate impact of changes in the independent variables on LNCDOE, while the long-term elasticities represent the equilibrium relationship between the variables. Furthermore, we consider the logic of the EKC theory using the concepts of Grossman and Krueger (1991), Narayan and Narayan (2010), and Gökmenoğlu and Taspinar (2016). Assuming that the long-term elasticity of LNGGR is negative or smaller compared to the short-term elasticity (Narayan and Narayan, 2010; Qi et al., 2019; Ridzuan et al., 2020) implies that LNGGR leads to lower LNCDOE, suggesting the presence of an EKC in the series (Narayan and Narayan, 2010; Al-Mulali et al., 2016; Gökmenoğlu and Taspinar, 2016).

Furthermore, the ECM provides insights into how the system adjusts toward long-term equilibrium. A noteworthy and negative ECM coefficient signifies a stable connection between LNCDOE and the independent variables, implying that any deviations from equilibrium will be gradually rectified over time. Additionally, the study examines serial correlation, heteroscedasticity, and normality tests recommended by (Narayan and Smyth, 2005; Sultanuzzaman et al., 2018) to check the model's goodness of fit. The research also scrutinizes the durability of the calculated model across the periods by employing diagnostic tests like the CUSUM & CUSUMSQ (Brown et al., 1975; Shahbaz et al., 2013; Pattak et al., 2023).

Subsequently, the study employs FMOLS and CCR models as alternative estimation techniques (Zimon et al., 2023), to assess the robustness of the ARDLF-BT approach in estimating long-run associations among variables in the existence of cointegration. ARDLF-BT is a flexible framework suitable for data with mixed orders of integration; however, it relies on assumptions of no endogeneity, serial correlation, or heteroscedasticity. FMOLS modifies the Ordinary Least Squares (OLS) estimator by incorporating a correction term for endogeneity and serial correlation, enabling consistent and efficient estimation of long-run parameters. CCR, on the other hand, addresses heteroscedasticity by employing an iterative procedure to estimate long-run parameters. Using FMOLS and CCR as robustness checks, we evaluate the sensitivity of the ARDL results

TABLE 3 Unit root test results.

Variable	Augmented dickey-fuller (ADF) test		Phillips-perron (PP) test	
	t-Statistic	Probability value	t-Statistic	Probability value
LNCDOE	−1.521	0.5232	−0.758	0.8313
ΔLNCDOE	−2.635	0.0000*	−5.311	0.0000*
LNGGR	−0.971	0.7637	−0.817	0.8141
ΔLNGGR	−3.300	0.0149**	−8.165	0.0000*
LNNRE	−1.785	0.3879	−0.762	0.8299
ΔLNNRE	−3.538	0.0071*	−6.736	0.0000*
LNRE	0.817	0.9919	1.388	0.9971
ΔLNRE	−9.470	0.0250**	−5.158	0.0000*
LNTEC	−1.826	0.3677	−2.169	0.2177
ΔLNTEC	−3.110	0.0258**	−8.898	0.0000*

Note: Δ denotes first difference, *I* (1), and *, and ** represent 1%, and 5% significance level.

to potential assumption violations (Chandio et al., 2020; Pattak et al., 2023). These models address econometric issues, enhancing the reliability of findings and strengthening the validity of results.

The study also employs VAR (Vector Autoregression) Granger causality tests to indicate mutual causality and direction between variables (Yii and Geetha, 2017; Qayyum et al., 2021). These tests help in designing effective interventions to address underlying causes. Granger causality tests also assist in model specification and predictive accuracy, identifying relevant variables, and improving forecasting performance. Furthermore, the study aims to forecast CDOE in Bangladesh from 1990 to 2030 using the VAR-IRF model (Christensen et al., 2021). This forecasting exercise allows for examining potential future trends in CDOE and their implications for green growth. Overall, the study provides empirical evidence of the consequence of CDOE on green economic growth, considering the explanatory variables of green growth, non-renewable energy, renewable energy, and technological efficiency. However, it's important to note that this explanation is a hypothetical scenario, and the specific results may vary depending on the actual data and methodology used in a particular study.

4 Findings and discussion

Empirical studies indicate that the relationship regarding green economic growth, structural economic issues, and emission issues differs depending on a country's characteristics. Some issues, such as the phase of economic development, the shape of technological progress, the type and intensity of energy use, and the utilization of natural resources, usually affect a country's CDOE.

Regarding this, we observe the influence of CDOE on the green growth of Bangladesh, operating different models such as ARDLF-BT, FMOLS, CCR, and Granger causality (VAR) models, as outlined by Chandio et al. (2020), Zimon et al. (2023), and Pattak et al. (2023), while additionally forecasting CDOE from 1990 to 2030 using the VAR-IRF model (Magazzino, 2014; Wang et al., 2022). Before conducting estimations, essential pre-estimation procedures are followed, including stationarity tests to ensure data suitability. The ADF and PP tests are applied, with a constant term included for accurate results. This assessment of variable stationarity helps prevent spurious regression and obtain reliable estimates (Narayan, 2005; Ghouse et al., 2018). To determine the significance level, a probability value of 0.10 (maximum) is adopted based on the work of S. R. Lee and Yoo (2016), enabling the identification of statistically significant relationships among the variables under investigation. The results divulge that all variables exhibit stationary properties at the I (1) level, indicating first-order integration (see Table 3). This is crucial for precise estimation and interpretation of the models, enhancing the reliability of the analysis. Expanding on the stationary aspects, F-bound techniques are operated to assess the long-term association among the variables. These techniques capture the persistent relationship between CDOEs, green growth, and energy sources, comprehensively understanding their interplay and implications.

The ARDLF-BT process scrutinizes the correlation between CDOE and various explanatory factors, including green growth, technological innovation, and non-renewable and renewable energy. As shown in Table 4, the estimated lag order suggests that the model incorporates lagged terms of the dependent and independent variables, capturing potential dynamic relationships and time dependencies (Pesaran et al., 2001).

The cumulative F-statistic (8.801) is statistically significant, surpassing the critical values at various significance levels ranging from 1% to 10%, as highlighted by Pesaran et al. (2001), Narayan and Smyth (2005) and Sultanuzzaman et al. (2018). Henceforward, a long-run equilibrium association between LNGGR, LNNRE, LNRE, LNTEC, and LNCDOE is clearly exhibited. By incorporating four lagged terms of the explanatory variables, which effectively account for delayed and time-dependent relationships, the analysis successfully captures the intricate dynamics of the variables. It is important to note that, as Narayan (2005) pointed out, if the generated F-values fall below the critical bounds, the theory's validity could be questionable. In light of this, this study addresses the concern. We now analyze the long-term impacts of

TABLE 4 ARDL F-bound Test Statistic.

ARDL F-bound Test Statistic Estimates by Pesaran et al. (2001) Critical Value	
Lag Order	4,1,2,2,3
F-Statistic	8.801

the relationships among LNCDOE, LNGGR, LNNRE, LNRE, and LNTEC using the ARDL computational approach.

The ARDLF-BT model's long-run elasticity coefficients for the green growth variable (−0.878) indicate a significant negative relationship (at the 5% level) between LNGGR and (Neve and Hamaide, 2017; Voumik et al., 2022; Lin and Ullah, 2024), as shown in Table 5. In contrast, these studies reveal opposing findings (Hondroyiannis et al., 2002; Lee and Yoo, 2016; Awosusi et al., 2022). A negative coefficient signifies an inverse association, implying that for each unit increase in green growth, LNCDOE decreases by approximately 0.878 units. These findings highlight the potential of policies and strategies aimed at promoting green growth, such as making renewable energy investments, improving energy productivity, and implementing environmental regulations to reduce LNCDOE and address climate change effectively (Price and Mckane, 2009; Sen and Ganguly, 2017).

These determinations reinforce the notion that balanced economic progress and environmental sustainability can be pursued in tandem. Adjusted net savings (green growth) highlights the importance of accounting for environmental externalities and the long-term sustainability of economic activities. By incorporating the costs associated with particulate emissions, the analysis captures a more comprehensive measure of green growth that incorporates the environmental consequences of economic development. Besides, focusing on green growth can generate employment in renewable energy, foster advancements in sustainable technologies, and improve resilience against climate impacts. By harmonizing economic incentives with environmental objectives, significant progress can be made in combating climate change while supporting sustainable development, ultimately benefiting future generations.

While the negative coefficient suggests that green growth is linked to reduced LNCDOE, it is crucial to consider potential trade-offs and unintended consequences. For instance, policies promoting green growth may lead to job displacement in specific industries, impact competitiveness, or have distributional effects. Alternatively, the short-run dynamics divulge that an increase of 0.474 units in LNGGR positively influences LNCDOE (Hussain and Dogan, 2021). Meanwhile, Bangladesh's shift towards green growth temporarily increases its total CDOE in the short term. This is due to the energy-intensive construction of renewable energy infrastructure and sustainable projects and the slower pace of green technology adoption compared to the phase-out of traditional carbon-intensive practices (Mondal et al., 2010).

Currently, Bangladesh's green growth strategy is maturing, and the economy is transitioning towards a lower-carbon development path (MPEMR, 2010). According to findings, green growth negatively correlates with CDOE, which extrapolates that sustainable economic growth can simultaneously reduce the

TABLE 5 ARDLF-BT model results on CDOE and influencing factor.

Variable	Coefficient	Standard error	t-Statistic	Probability value		
Long-run						
LNGGR	−0.878	0.370	−2.370	0.039**		
LNNRE	3.908	1.077	3.630	0.005*		
LNRE	3.130	1.258	2.490	0.032**		
LNTEC	−0.174	0.097	−1.800	0.102		
Constant	−7.776	5.995	−1.300	0.224		
Short-run						
ΔLNGGR	0.474	0.153	3.090	0.011**		
ΔLNNRE	2.352	0.911	2.580	0.027**		
ΔLNRE	3.934	1.415	2.780	0.019**		
ΔLNTEC	0.166	0.073	2.280	0.046**		
ECM	−0.827	0.281	−2.940	0.015**		
Diagnostic Tests of ARDL Model						
Breusch-Godfrey Auto-correlation Lagrange Multiplier (LM) Test				1.789 (0.4088)	R^2	0.9668
Heteroscedasticity: Breusch-Pagan-Godfrey				28.00 (0.4110)	Adjusted -R2	0.9136
Jarque-Bera				1.188 (0.5521)	CUSUM	Fit
Durbin-Watson				2.2202	CUSUMSQ	Fit

Note: *and ** represent 1%, and 5% significance levels, and diagnostic tests' probability values are in parentheses.

country's carbon footprint in the long run. Over time, the increased use of renewable energy sources, energy-efficient technologies, and other green initiatives leads and will lead to a decline in Bangladesh's overall CO_2 emissions. These findings underscore the importance of prioritizing policies and strategies that foster green growth and sustainable practices to facilitate Bangladesh's transition to a low-carbon future. Correspondingly, implementing these green initiatives within climate change strategies will strengthen resilience to climate impacts, ensuring that economic growth aligns with environmental sustainability. By effectively pursuing environmental, social, and economic goals, Bangladesh can address climate change and enhance green economic development.

Respectively, the study divulges that increased LNNRE usage significantly exploits LNCDOE in the short and long term. Whereas a unit increase in non-renewable energy usage leads to a nearly four-unit (3.908) increase in LNCDOE in the long run as (Bekun et al., 2019; Lee and Yoo, 2016; Bekun et al., 2019; Ben Jebli and Ben Youssef, 2015; Awosusi et al., 2023). Similarly, while in the short run, it corresponds to a 2.352-unit increase. These findings underline the need to shift to renewable energy sources to address climate change. Dependence on non-renewable fossil fuels obstructs GHG reduction efforts. To tackle climate change effectively, it is crucial to implement policies actively and allocate investments that foster the adoption of renewable energy technologies, including wind, solar, and hydroelectric power. Reducing reliance on non-renewable energy and promoting cleaner alternatives can mitigate CDOE and contribute to a sustainable and climate-resilient future. This transition is crucial for achieving long-term climate change mitigation goals.

Table 5 even depicts a positive link between increased LNRE and higher LNCDOE in the long and short run (Mathiesen et al., 2011; Tiwari et al., 2015; Bekun et al., 2019), nevertheless, the results diverge from these studies (Suki et al., 2022; Xie et al., 2022; Ibrahim et al., 2023; Anser et al., 2024). Specifically, in the long run, a one-unit increase in LNRE is linked to a 3.130-unit rise in LNCDOE (Tiwari et al., 2015). In the short run, a one-unit increase in LNRE results in a 3.934-unit increase in LNCDOE (Mathiesen et al., 2011; Tiwari et al., 2015). This positive relationship may seem counterintuitive, but this can be attributed to the initial phases of the transition to renewable energy, during which traditional non-renewable energy sources continue to coexist with renewables. Optimizing the existing infrastructure is necessary to reduce inefficiencies and emissions. Additionally, the indirect effects of renewable energy adoption, such as promoting green economic growth and industrial activities, contribute to higher overall energy consumption and subsequent CDOE. For the future, implementing effective renewable energy policies, utilizing advanced technology, and domestic and foreign investment in the energy sector are crucial to rapid growth (Joo et al., 2015) and diminishing CDOE (Mathiesen et al., 2011). These measures positively impact the economy, creating jobs, fostering sustainable energy practices (Mathiesen et al., 2011), and promoting sustainable green growth for this nation. By aligning climate mitigation strategies with economic development initiatives, Bangladesh can enhance resilience to climate impacts while fostering sustainability that reduces its carbon footprint and sets a benchmark for other countries in addressing climate change as well.

In the long term, Table 5 indicates that a one-unit rise in LNTEC is linked to a 0.174-unit reduction in LNCDOE, suggesting a possibility of reduced emissions (Hussain and Dogan, 2021; Lin and Ullah, 2024). The economy fuels green growth through investments in sustainable technologies and practices such as renewable energy, efficient resource use, eco-friendly farming, and waste reduction, all aimed at reducing environmental impact. Besides, short-term results authenticate that a one-unit escalation in LNTEC directs to a 0.166-unit rise in LNCDOE. Economic growth frequently leads to higher energy usage and emissions due to higher demand and industrial activities. However, with the right policies, economic growth can be decoupled from environmental degradation by adopting green technologies and sustainable practices (Lin and Ullah, 2024). Prioritizing sustainable economic growth, promoting green technologies, and integrating environmental considerations into decision-making are vital. This way, Bangladesh can drive green growth, lessen CDOE, mitigate climate change, and conserve natural resources (Dinda, 2018; Chen et al., 2023; Zhao et al., 2023).

Moreover, the presence of a turning point in the connection between green growth and CDOE offers valuable insights into the EKC theory. When the long-term factor of green growth (LNGGR) is negative on LNCDOE, it confirms the existence of an EKC relationship, in line with prior studies (Adila et al., 2021; Barbier, 2003; Jahanger et al., 2022; Kim et al., 2018; Luo et al., 2021; Xie et al., 2022; Yavuz, 2014), while some studies present contradictory findings (Abokyi et al., 2019; Hasanov et al., 2019). Although, this turning point represents a critical threshold where additional green economic growth guides the reduction of CDOE and enhanced environmental quality in Bangladesh. Identifying the turning point is crucial for policymakers as it guides the establishment of specific targets for green growth and emissions reduction, promoting sustainable development. Prioritizing investments in green technologies accelerates the transition towards the turning point. Implementing regulations, encouraging sustainable investments, and promoting public awareness campaigns further support this transition. Strengthening international cooperation is essential for addressing climate change and promoting global sustainable development. Bangladesh is currently grappling with the rising tendency of CDOE due to its low level of industrialization. However, the country is undergoing reindustrialization with technological progress and has undertaken renewable energy projects to mitigate global pollution (Uddin et al., 2019). Efforts toward energy-efficient industrialization, supported by appropriate policies, technologies, and institutional frameworks, instill hope for Bangladesh's low-carbon future and sustainable green growth. Environmental qualities are crucial for the sustainable economic development. Meanwhile, ongoing initiatives and advancements in Bangladesh's industrialization and renewable energy sectors offer hope for a future that is greener and more sustainable.

The Error Correction term (ECM) in the ARDLF-BT approach provides insights into the adjustment process towards the long-run equilibrium. Thus, the computed ECM of −0.827 is highly significant and negative, indicating a swift correction of deviations from the long-run equilibrium (see Table 5). This suggests that if short-term deviations exist from the equilibrium relationship between CDOE and the explanatory variables, adjustments will occur to restore the equilibrium. The system acts to reduce CDOE and align them with the 82.7% equilibrium level. The magnitude of the ECM (−0.827) signifies a rapid adjustment process towards the long-run equilibrium, demonstrating strong restorative forces that quickly bring CDOE in line with the equilibrium relationship. This equilibrium

TABLE 6 FMOLS and CCR analysis of CDOE and influencing factors.

Variable	Fully modified least squares (FMOLS)	Canonical cointegration regression (CCR)
LNGGR	−0.321* (0.004)	−0.278* (0.003)
LNNRE	2.799* (0.009)	1.974* (0.006)
LNRE	1.998* (0.012)	0.835* (0.008)
LNTEC	−0.457* (0.002)	−0.126* (0.001)
Constant	−0.684* (0.055)	3.671* (0.041)

Note: * represents a 1% significance level, and standard errors are in parentheses.

relationship relates to Bangladesh's green growth, energy sources, and technological innovation.

The ARDLF-BT model equips useful statistics to assess its sensitivity (see Table 5). The R^2 statistic insinuates that the independent variables explain approximately 96.68% of the variance in CDOE, exemplifying strong explanatory power. The adjusted R^2, considering model complexity, proposes that the explanatory variables explain around 91.36% of the variation. The Durbin-Watson statistic (2.22) points out no significant autocorrelation in the residuals, indicating the model accounts for temporal dependence. The insignificant outcomes of the Breusch-Pagan-Godfrey and Breusch-Godfrey autocorrelation LM tests imply no evidence of heteroscedasticity or higher-order autocorrelation, respectively (Narayan and Smyth, 2005; Ahmad and Du, 2017; Pata and Isik, 2021; Darsono et al., 2022). The insignificance of the Jarque-Bera statistics indicates adequate capturing of data distribution properties. Overall, the insignificant sensitivity outcomes support the model's adequacy in capturing relationships, absence of serial correlation, heteroscedasticity, and adherence to normality assumptions (Etukafia et al., 2017; Khan et al., 2019; Assi et al., 2021). Additionally, the CUSUM and CUSUMSQ graphs falling within the black dots at a 5% significance level confirm the stability of the ARDL method, suggesting reliable and consistent coefficient estimates over time (Figures will be provided upon request) (Brown et al., 1975; Shahbaz et al., 2017; Zimon et al., 2023).

4.1 Robustness checks

The FMOLS and CCR models yield the same results as the ARDLF-BT model robustness test context, which is significant and provides essential insights (Table 6). The convergence of results across both estimation techniques strengthens the validity of the ARDLF-BT findings (Pata, 2018). It provides additional evidence for the long-run affinity between CDOE, green growth, energy sources, and technology under investigation. The relationship between the variables remains consistent regardless of the specific estimation technique employed. This finding enhances the confidence in the reliability of the ARDLF-BT model's results.

4.2 VAR granger causality wald test

The VAR Granger Causality results, as presented in Table 7, provide valuable insights into the direction of causality among the examined variables. The significance levels, denoted by asterisks (*), represent the strength of the relationships, with a significance level of 1%. Multiple relationships exhibit bidirectional causality, indicating mutual influence between the variables.

TABLE 7 Granger causality test results.

Causality	Wald test (chi^2)	Decision
LNCDOE → LNGGR	35.412*	Bidirectional Causality
LNGGR → LNCDOE	13.879	
LNCDOE → LNNRE	30.413*	Bidirectional Causality
LNNRE → LNCDOE	16.84*	
LNCDOE → LNRE	33.61*	Bidirectional Causality
LNRE → LNCDOE	14.329*	
LNCDOE → LNTEC	9.543*	Bidirectional Causality
LNTEC → LNCDOE	38.264*	
LNGGR → LNNRE	17.226*	Bidirectional Causality
LNNRE → LNGGR	27.457*	
LNGGR → LNRE	24.304*	Bidirectional Causality
LNRE → LNGGR	28.633*	
LNGGR → LNTEC	13.495*	Bidirectional Causality
LNTEC → LNGGR	67.878*	
LNNRE → LNRE	8.21**	Bidirectional Causality
LNRE → LNNRE	12.382*	
LNNRE → LNTEC	23.975*	Bidirectional Causality
LNTEC → LNNRE	84.034*	
LNRE → LNTEC	45.91*	Bidirectional Causality
LNTEC → LNRE	81.859*	

Note: * and ** represent 1%, and 5% significance level.

The findings highlight bidirectional causality between LNCDOE (carbon emissions) and LNGGR (green growth), suggesting that changes in LNGGR significantly impact LNCDOE and *vice versa*. A similar bidirectional causality is observed between LNCDOE and LNNRE (non-renewable energy consumption), indicating a reciprocal correlation among variables. The same pattern holds for LNCDOE and LNRE (renewable energy consumption), as well as LNCDOE and LNTEC (technological progress). Furthermore, bidirectional causality is identified between LNGGR and LNNRE, LNGGR and LNRE, LNGGR and LNTEC, LNNRE and LNRE, LNNRE and LNTEC, and LNRE and LNTEC. These results suggest that changes in LNGGR, LNNRE, LNRE, and LNTEC exert significant influences on one another, indicating a mutually reinforcing relationship.

These findings underscore the interconnectedness and interdependence of variables related to CDOE, green growth, non-renewable and renewable energy consumption, and technological progress. The bidirectional causality implies that alterations in these variables have reciprocal effects on one another. This understanding can help policymakers, collaborators, and stakeholders formulate comprehensive strategies and policies that consider the complex dynamics of these variables. By recognizing the bidirectional causality, policymakers can work towards promoting sustainable development by simultaneously addressing multiple aspects, including fostering green growth, reducing CDOE, and promoting renewable energy and technological advancements. Meanwhile, ensuring an adequate supply of energy and effective use of technology-efficient energy resources may dynamically generate green growth in Bangladesh. In particular, technology is a crucial driver of the economy, enabling income growth while reducing emissions (Dinda, 2018). Technology and renewable energy can positively stimulate Bangladesh's green growth. Therefore, these outcomes imply that this ARDL analysis robustly examines the effects and yields the most suitable results for this study.

4.3 CO_2 emissions (CDOE) forecasting

The study forecasts Bangladesh's CDOE from 1990 to 2030 using the VAR-IRF methodology, acknowledging that unpredictable factors such as technological changes and innovations, policy decisions and regulations, and economic conditions and developments can impact the emissions trajectory. The solid line shows a consistent upward trend in CDOE, projected to continue in Bangladesh (see Figure 1). The shaded regions represent uncertainty due to these factors, like technological changes, policy decisions, and economic conditions. Additionally, the upper bound (UB) and lower bound (LB) offer estimated emission ranges for 2021–2030, highlighting the importance of considering uncertainty. The government should develop flexible, adaptive policies that can be adjusted as conditions evolve. They should conduct scenario planning and risk management to prepare for emissions pathway uncertainties. Policymakers should establish monitoring systems to review and refine policies based on data. They should also strengthen stakeholder engagement to enhance policy responsiveness. Policymakers can use the CDOE forecast for informed decision-making, targeted policies, and emission reduction measures. This entails promoting renewables, improving energy efficiency, implementing carbon pricing, supporting sustainable transportation, and adopting green technology. Addressing climate change requires concerted efforts to limit global warming and its impacts by reducing CDOE. Sustainable, low-carbon growth strategies play a vital role in achieving this goal and building a resilient future in Bangladesh.

Overall, this research highlights the urgent need for effective policies to assist Bangladesh in transitioning from non-renewable to renewable energy sources, which is crucial for managing complex

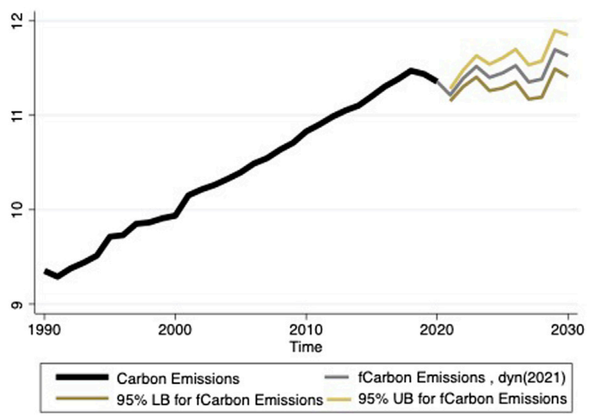

FIGURE 1
Navigating Bangladesh's carbon future: Emissions projections amidst uncertainty.

interconnections among various factors. The government should introduce financial incentives, such as tax deductions and subsidies, to encourage the adoption of renewable technologies like solar, wind, and biomass. Establishing energy efficiency standards and green building regulations will further facilitate this shift, while increased funding for research and development can help address issues related to agricultural emissions and urban pollution.

A robust framework for integrating renewable energy is essential, requiring careful planning of the energy mix and setting mandatory targets for electricity providers, including the Bangladesh Power Development Board (BPDB) and private firms like Summit Power. Key initiatives could involve developing a national renewable energy roadmap outlining schedules for solar and wind projects nationwide. Setting performance benchmarks in sectors such as transportation and manufacturing can direct progress while prioritizing renewable technologies in electricity generation and agriculture, which will help accelerate the transition. Regulations that mandate emissions reductions in industries, combined with carbon pricing, will motivate companies to innovate and decrease their carbon footprints. Drawing lessons from the experiences of countries like Denmark, Germany, and Costa Rica can offer valuable insights for Bangladesh's initiatives.

Furthermore, Bangladesh is enhancing its forestry sector through the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) framework to aid climate change mitigation. This effort includes estimating emissions, creating a monitoring system, and targeting an increase in forest area from 22%–25% by 2030 (MEFCC, 2023). Implementing adaptation strategies, such as climate-resilient infrastructure and sustainable agricultural practices, will strengthen the nation's ability to cope with climate-related challenges. By prioritizing these strategies, Bangladesh can effectively fulfill its climate commitments under the Paris Agreement while promoting sustainable development and environmental stewardship.

5 Conclusion

This study conducted an extensive analysis of the relationship between green growth, energy sources, technological innovation, and CDOE in Bangladesh from 1990 to 2020 using the ARDLF-BT model. The empirical findings provide several important insights.

Firstly, the study ascertained a negative association between green growth and CDOE, highlighting the compatibility and mutual reinforcement of economic development and environmental sustainability in the long run. Conversely, in the short run, green growth positively influences CDOE in Bangladesh, indicating that as the country focuses on promoting sustainable economic growth, it can simultaneously reduce its carbon footprint. These findings underscore the significance of prioritizing policies and strategies that foster green growth and sustainable practices to pave the way for a low-carbon future in Bangladesh.

Secondly, the study demonstrated that non-renewable energy has a detrimental impact on CDOE, emphasizing the importance of transitioning to renewable energy sources like solar, wind, hydro, and nuclear power. This transition can significantly reduce GHGs and provide to global climate change mitigation efforts in the short and long run.

Thirdly, although a positive correlation between renewable energy and CDOE was observed in the short and long run, optimizing existing renewable energy infrastructure is crucial. This involves improving the efficiency of renewable energy production and distribution systems as well as ensuring a seamless shift from non-renewable to renewable sources.

Lastly, the study highlighted the negative impact of CDOE associated with technological progress, emphasizing the importance of sustainable technology innovation in the long run. Investing in research and developing clean technologies can foster economic growth while minimizing carbon footprints. However, the short-term outcomes suggest that green economic growth often increases energy consumption and emissions due to higher demand and industrial activities.

The FMOLS and CCR models yielded results similar to the ARDLF-BT model, validating the findings. VAR Granger causality analysis emphasized the interconnectedness of variables related to CDOE, green growth, non-renewable and renewable energy consumption, and technological progress. Policymakers and stakeholders can use these insights to develop comprehensive strategies and policies that address the complex dynamics among these variables. The VAR-IRF findings reveal an upward trend in CDOE, underscoring the need for urgent action. Uncertainties in technology, policies, and the economy must be managed through effective risk strategies. Sustainable, low-carbon approaches incorporating optimal energy utilization, renewable energy, energy conservation, and international collaboration are vital. Bangladesh's efforts contribute to global emission reduction and build a resilient future.

To enhance climate change mitigation in Bangladesh, the government should prioritize financial incentives, including tax breaks and subsidies, to promote renewable energy adoption. Establishing energy efficiency standards and increasing funding for research and development will be crucial in addressing local issues such as agricultural emissions and urban pollution. Additionally, public awareness campaigns and global partnerships can promote sustainable practices while focusing on renewable technologies in sectors like power generation, transportation, and agriculture will accelerate the transition. Strategic energy planning, which includes mandatory renewable energy targets and investments in energy storage, will facilitate a reliable shift to cleaner energy sources.

By adopting these policy recommendations, Bangladesh can significantly reduce CDOE, advance green growth, and contribute to global climate initiatives. A comprehensive approach that combines policy interventions, technological innovations, and public engagement is vital for achieving sustainable development goals. Furthermore, increasing investment in renewable energy strategies and implementing advanced energy-efficient technologies are essential steps toward sustainable growth. Strengthening regional commitments to environmental agreements, managing transboundary pollution, and promoting sustainable resource management and forest conservation will also play critical roles in this effort.

This study has several constraints, notably its dependence on data from 1990 to 2020, which may not reflect current trends in green growth and energy use. Although the ARDL method is a solid approach, it might miss non-linear relationships and overlook confounding factors, which could compromise the accuracy of the findings. Furthermore, the exclusive focus on Bangladesh restricts the applicability of the results, as other nations may demonstrate different interactions between energy sources and CDOE. Future investigations should broaden the dataset to include years beyond 2020, engage in cross-country comparisons, and utilize non-linear models and sector-specific assessments. Additionally, evaluating the effectiveness of specific policies will enhance the understanding of carbon emissions and the influence of green growth and energy sources on climate change mitigation.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: World Bank and OECD Database.

Author contributions

SA: Methodology, Data curation, Conceptualization, Writing–review and editing, Writing–original draft. MS: Writing–review and editing, Formal Analysis. YZ: Writing–review and editing, Supervision. FA: Writing–review and editing, Funding Acquisition. MH: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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