frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 26 March 2025
DOI 10.3389/fenvs.2025.1525281

New insights into how green innovation, renewable energy, and institutional quality shape environmental sustainability in emerging economies

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RECEIVED 11 November 2024
ACCEPTED 12 March 2025
PUBLISHED 26 March 2025

CITATION
Gan J (2025) New insights into how green innovation, renewable energy, and institutional quality shape environmental sustainability in emerging economies.
Front. Environ. Sci. 13:1525281.
doi: 10.3389/fenvs.2025.1525281

The development of green innovation in achieving Sustainable Development Goals (SDGs) is gaining popularity in recent works. However, the perspective from emerging economies is limited leaving them behind in the drive toward global sustainability. Therefore, this study provides new insights into how green innovation development and the quality of institutions have influenced green energy adoption and overall Sustainability using 30 emerging economies from 1990 to 2020. The study employs three econometric models—Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Ordinary Least Squares (OLS) to make a comparative analysis. The findings show the varying and pivotal role of technological advancements, institutions, and green energy in reducing carbon footprints based on models. Notably, it was found that green innovation had a positive effect (FMOLS), and negative effect (DOLS and OLS) on CO_2 emissions. Renewable energy had a negative effect (FMOLS and OLS), and a positive effect (DOLS) on CO_2 emissions. Again, institutional quality showed a positive effect (DOLS and FMOLS) and a negative effect (OLS) on CO_2 emissions. The study believes the DOLS model exhibited the most robust explanatory power, with the highest explanatory power of 99.9%. These results provide greater insights and the comprehensive policies outlined can help policymakers formulate working policies to bolster green innovation, improve green energy development, and strengthen institutional frameworks toward achieving overall SDGs.

KEYWORDS

sustainable development, green innovation, emerging economies, sustainable economies, institutions

1 Introduction

The escalating environmental concerns surrounding climate change have elevated the need for comprehensive strategies to mitigate carbon dioxide (CO_2) emissions (Aziz et al., 2024). Among the principal drivers of climate change, CO_2 emissions represent the largest share of global greenhouse gases, primarily stemming from energy production, industrial activities, and deforestation (Borowiec and Papież, 2024). In response to these challenges, governments, industries, and policymakers are increasingly focusing on sustainable development approaches. For emerging economies, achieving sustainable development has become an urgent priority due to rapid industrialization, urbanization, and environmental degradation. Policymakers are increasingly promoting green innovations and renewable energy as pathways toward low-carbon, sustainable growth. However, while the link between environmental technologies and sustainable development has been explored extensively, the role of institutional quality in enhancing or constraining this relationship remains underexplored. Institutions, which include governance frameworks, regulatory effectiveness, and anti-corruption measures, play a vital role in creating a conducive platform for green innovation (GIN) and sustainable energy acceptance. This study, therefore, seeks to uncover how these three elements—green innovation, institutional quality, and renewable energy (REG)—interact to influence sustainable development outcomes in emerging economies.

Green innovation, which refers to the development and implementation of environmentally friendly technologies and practices, is central to reducing emissions and promoting a low-carbon economy (Obuobi et al., 2024). This concept encompasses innovations in energy efficiency, waste reduction, and the transition to cleaner production processes. Despite its potential, the degree to which green innovation reduces CO_2 emissions depends on supportive institutional frameworks, policy consistency, and market acceptance (Amin et al., 2023). In this study, institutional quality (IQ) is defined as government effectiveness in promoting environmental sustainability through regulatory effectiveness, transparency and accountability, and policy stability. These dimensions ensure strong enforcement of environmental regulations, reduce corruption and create a stable policy environment for green investments and innovation. Institutional quality plays a critical role in the effectiveness of emission reduction efforts by shaping the enforcement of environmental regulations, promoting transparency, and ensuring policy stability (Azam et al., 2022). Strong institutions foster the implementation of green innovations and renewable energy policies by reducing barriers such as corruption and policy uncertainty (Amin et al., 2023). In contrast, weak institutions can undermine progress by creating inefficiencies and regulatory loopholes (Sun et al., 2019). The interaction between institutional quality (IQ) and other environmental strategies, however, remains complex and warrants further investigation to unravel the synergies and constraints it may present. Simultaneously, the shift towards renewable energy sources—such as wind, solar, and hydropower—offers a viable solution for reducing CO_2 emissions by replacing fossil fuel-based energy systems. Many countries have intensified investments in renewable energy to meet global climate goals (Akan et al., 2023), but these efforts require sustained technological innovation and institutional support to overcome challenges related to scalability, grid integration, and energy storage. Gaining insights into how green innovation and governance systems play out is key for designing suitable climate mitigation policies. It raises the following questions to be examined in the study. (1) How does green technology innovation influence carbon emissions in emerging economies? (2) How has renewable energy development impacted carbon emissions in emerging economies (3) How does the quality of institutions and environmental policies in emerging economies influence their carbon emissions?

These questions give rise to the objectives of this study is to examine how green innovation, institutional quality, and renewable energy adoption collectively influence environmental sustainability. While existing literature has extensively explored the relationship between green innovation, renewable energy, and CO_2 emissions, there remains a significant gap in understanding the role of institutional quality in moderating these relationships, particularly in emerging economies. Again, most studies focus on developed economies, leaving a limited understanding of how context-specific governance challenges in emerging economies influence sustainability outcomes. Additionally, the interplay between green innovation, renewable energy, and institutional quality has not been adequately examined. This study fills these gaps by providing a comprehensive analysis of how these factors collectively influence environmental sustainability in 30 emerging economies. Past studies have emphasized how green innovativeness and clean energy mitigate ecological footprints. For instance, studies by Xie and Jamaani (2022) and Acheampong et al. (2022) confirm the positive relationship between these factors and sustainable development. However, these and many other studies often adopt a narrow focus on technological solutions, treating the institutional environment as a background factor rather than a core element influencing sustainable outcomes. Institutional frameworks characterized by poor governance, lack of accountability, and inconsistent policy enforcement affect sustainability efforts including green innovations and renewable energy investments. Additionally, while institutional quality has been acknowledged in other studies, its relevance in fostering sustainability through green technologies and renewables has not received adequate attention. The existing literature that does address green innovation and institutional quality in this context tends to focus on developed economies, with little focus on emerging economies. Therefore, this study is novel in two ways. First, it examines the collective impact of green innovation, institutional quality, and renewable energy on environmental sustainability in emerging economies. Second, it adopts three advanced econometric models to make a comparative analysis. By employing advanced econometric models (FMOLS, DOLS, and OLS), the study offers novel insights into the dynamic relationships among these variables, contributing to both academic discourse and policy formulation. It offers empirical evidence on the significance of institutional quality in driving sustainable development through green technologies. It provides a basis for future studies on the topic under discussion. Furthermore, the research highlights how context-specific governance challenges in emerging economies influence the success of sustainability initiatives, addressing an area that remains under-researched in existing studies. Lastly, it offers timely insights for policymakers and stakeholders in emerging economies to formulate policies aimed at promoting green innovation and strengthening institutional quality.

The following sections are outlined accordingly: Chapter 2 presents the literature review. Subsequently, the methodology section outlines the data and econometric techniques employed. Next, the empirical results, and discussion and presented, and finally conclusion and policy implications are presented

2 Literature review and theoretical basis

2.1 Theoretical framework

The theoretical foundation of this study is anchored in the Environmental Kuznets Curve (EKC), which posits that environmental degradation initially intensifies with economic growth but eventually declines as economies transition towards cleaner technologies and stronger regulatory frameworks (Beyene, 2022; Danish and Ulucak, 2021). This inverted U-shaped relationship suggests that while industrialization and economic expansion may initially lead to increased carbon emissions, sustained growth, technological advancements, and institutional interventions can drive long-term environmental improvements (Işık et al., 2019). Many emerging economies are at the initial growth stages and are experiencing high emissions, which makes green innovation and energy relevant to their growth to ensure their pollution levels declines as they grow.

Complementing the EKC, Institutional Theory underscores the critical role of governance, regulatory policies, and institutional quality in shaping environmental and economic outcomes (Forster et al., 2025). This theory posits that well-functioning institutions—through stringent environmental policies, incentives for green investments, and enforcement of emission regulations—can effectively moderate the impact of industrial activities on carbon emissions (Yang et al., 2024). Institutional strength, in this regard, determines the extent to which nations can successfully implement and sustain green policies, ensuring that economic growth does not come at the expense of environmental sustainability. This theory guides the development of emerging economies in Technologies and sustainable growth.

Furthermore, the Innovation Diffusion Theory (IDT) provides a lens through which the adoption and spread of green technologies can be understood. The IDT explains how innovations—such as renewable energy solutions and eco-friendly industrial practices—are disseminated within societies and industries (Ayanwale and Ndlovu, 2024). The rate of adoption is influenced by factors such as perceived benefits, technological readiness, regulatory support, and social acceptance. In the context of this study, IDT helps explain how green technological advancements contribute to reducing carbon emissions and enhancing sustainability in emerging economies.

Together, these three theoretical perspectives—the EKC, Institutional Theory, and IDT—offer a holistic framework for analyzing the intricate relationships between green innovation, renewable energy adoption, institutional quality, and CO_2 emissions in emerging economies. By integrating these perspectives, this study provides an understanding of how economic structures, policy frameworks, and technological advancements collectively shape environmental outcomes. The following subsections review relevant empirical studies grounded in these theories to guide the development of hypotheses for this research.

2.2 Green innovation and CO_2 emissions

Green innovation is key in reducing CO_2 emissions by enhancing production processes through energy efficiency, cleaner technologies, and environmentally friendly practices (Xie and Jamaani, 2022). Studies show that green technological innovations significantly impact sectors with high carbon footprints, such as transportation, manufacturing, and energy production. For instance, (Dong et al., 2023), demonstrate that countries with active green innovation policies see a marked increase in emission efficiency over time, especially those committed to carbon neutrality targets. Also, (Amin et al., 2023), indicate that the benefits of green technologies are most apparent in the medium to long term as institutions adopt these technologies at scale. In recent years, studies have increasingly analyzed the impact of green innovation on CO_2 emissions across different regions, sectors, and timeframes, with numerous studies revealing diverse outcomes. For example, (Yuan et al., 2022), explored in China, the regional impact of GIN on CO_2 emissions. The findings indicated a substantial CO_2 emissions reduction caused by GIN, particularly in the eastern and western regions. In the Western region, the effectiveness of green innovation in decreasing emissions was enhanced by improvements in institutional quality. Furthermore, a temporal analysis shows that the effect of GIN on emissions reduction was more noticeable between 2013 and 2017 compared to the 2005–2012 period. During the earlier phase, the increase in institutional quality seemed to weaken green innovation's effectiveness, whereas in the latter period, institutional enhancements amplified the positive impact of green initiatives. Similarly, a study by (Zhang et al., 2021) was conducted from 2004 to 2018 to assess how GIN policies influenced carbon emissions in China. The research concluded that policies fostering green innovation were effective in reducing emissions. Moreover, these policies significantly boosted the efficiency of industrial green innovation, thus promoting sustainable economic growth.

Research in other regions, such as (Albaker et al., 2023) study in MENA countries, adds further dimensions to the discourse. By employing advanced quantitative methods, the study highlighted that GIN plays a crucial part in reducing emissions across various economic quantiles, with consistent results validated by multiple robustness checks. Furthermore, Granger causality tests confirmed the existence of a bidirectional link between GIN and carbon emissions in the region. In another notable study, (Liu et al., 2022a), investigated the effectiveness of green innovation across 30 Chinese provinces from 2000 to 2019 using both fixed-effects and Spatial Durbin models. The analysis concluded that green innovation significantly reduces carbon emission intensity, with positive spillover effects observed when adjacent cities also improve their green innovation capacities. This suggests that localized green efforts can benefit broader regional carbon reduction goals. Also, (Xu et al., 2021), conducted research focused on the effect of GIN on CO_2 emission performance in 218 Chinese cities from 2007 to 2013. The study found that various forms of GIV positively influence CO_2 emission performance, although the effectiveness varied. Notably, direct carbon-reduction innovation and administrative green policies were less impactful compared to other green innovations, indicating heterogeneity in the effectiveness of green innovation across different urban environments.

Additionally, (Chen et al., 2021), examined the implications of China's carbon trading scheme, focusing on its influence on green innovation. The analysis, which utilized data from 1990 to 2018, found that the anticipated positive effect of green patents had not materialized, with small-scale and manufacturing enterprises showing a tendency to reduce production rather than innovate. This lagging effect of the carbon trading policy was especially pronounced among smaller, non-state-owned businesses in the eastern and central regions of China. The study underscored that the financial constraints and reduced cash flow resulting from the policy led to diminished investments in research and development, thereby limiting green technological innovation.

In the construction sector, (Li et al., 2023a), assessed the carbon-reducing capabilities of green innovation. The research highlighted that green innovation has a substantial positive effect on CO_2 emissions, particularly in the presence of environmental regulations. The results also indicated that the influence of green innovation on carbon reduction varied according to regional, developmental, and innovation factors. Moreover, (Wang et al., 2023), examined the connection between CO2 emissions and GIN among SMEs. It was observed that companies often preferred green innovation strategies with lower barriers to entry and greater practical benefits. The study also revealed that regions with deeper digital finance integration showed superior results in reducing carbon emissions, emphasizing the need for raising green innovation standards and encouraging more substantial green practices.

Further research by (Liu et al., 2022b) utilized a spatial difference-in-differences (SDID) model to investigate the relationship between green innovation and carbon emissions, demonstrating that green innovation contributed to a comprehensive reduction in emissions. This spatial approach underscored the importance of accounting for regional interdependencies in understanding the efficacy of green initiatives. Finally, a study by Xie and Jamaani (2022) explored the G-7 economies over three decades. The results confirmed that green innovation significantly mitigated carbon emissions, with results consistently validated across different quantiles. This underlines the versatility of GIN in addressing emission mitigation goals in diverse economic contexts, even among advanced economies. Existing literature demonstrates a complex but generally highlighting that green innovation has a mitigating effect on carbon emissions. While the specific impact of green innovation varies by region, economic sector, and policy environment, the overall evidence supports its potential to drive sustainable development and lower carbon footprints. Therefore, this study also hypothesizes that.

Hypothesis 1: *Green innovation significantly reduces CO_2 emissions in emerging economies.*

2.3 Renewable energy and CO_2 emissions

The deployment of renewable energy sources, such as solar, wind, and hydroelectric power, has been recognized as one of the most effective ways to reduce CO_2 emissions (Al-Ismail et al., 2023). Renewable energy displaces carbon-intensive fossil fuels, hom thus decreasing the carbon intensity of energy production. Chen et al. (2023) show that renewable energy consumption has a long-term negative impact on CO_2 emissions, especially when implemented alongside energy-efficient practices and smart grids. However, the transition to renewables is not without challenges, particularly in emerging economies (Zhou et al., 2023). The high upfront cost of installing renewable energy infrastructure often limits its adoption. Moreover, integrating renewable energy into national grids requires technical expertise, advanced storage technologies, and a reliable policy framework—elements that many developing countries struggle to maintain.

Several research has investigated the relationship between renewable energy and CO_2 emissions with mixed results. For instance, (Chen et al., 2023), conducted a comprehensive study on the relationship between renewable energy use and air pollution in China over the period from 1990 to 2022, employing Granger causality analysis. The findings revealed a clear unidirectional causality, where increased renewable energy adoption directly contributed to a reduction in air pollution. Despite significant government investments aimed at expanding renewable energy, the research underscored China's persistent dependency on conventional energy sources, suggesting that traditional fuels still play a dominant role in the economy. Moreover, (Zhou et al., 2023), investigated the influence of renewable energy on carbon emissions in four emerging Asian economies between 2010 and 2021. The study utilized a cross-sectional autoregressive distributed lags model combined with a dynamic common correlated effects estimator to tackle challenges related to cross-sectional dependence, endogeneity, non-stationarity, and heterogeneous slopes. The results indicated that renewable energy significantly reduces carbon emissions, enhancing these nations' capabilities to meet their carbon neutrality objectives. Also, (Hasni et al., 2023), explored the impact of REG on CO_2 emissions in 18 APEC economies from 2000 to 2019. The analysis revealed that REG adoption plays a key part in mitigating CO_2 emissions across these economies, although the extent of its impact varies depending on regional and economic contexts.

Again, (Naeem et al., 2023), assessed the link between clean energy initiatives and CO_2 emissions reduction in 24 OECD nations over a two-decade span, from 2000 to 2020. The study highlighted that expanding access to renewable energy leads to notable decreases in carbon emissions, indicating that clean energy investments are an effective tool for lowering the carbon footprint in developed economies. Also, (Waris et al., 2023), examined the ASEAN region from 1990 to 2021, focusing on the effectiveness of renewable energy in mitigating carbon emissions in low to medium-income emerging economies. By employing the Method of Moments Quantile Regression, the findings showed that renewable energy utilization significantly reduces carbon emissions, particularly in countries with emerging economies that are striving to balance economic growth with sustainability. Similarly, (Li et al., 2023b), conducted a global analysis across 130 countries from 1992 to 2019. The study found a negative correlation between REG and ecological footprint and CO_2 emissions. This indicates that as REG consumption increases, its effectiveness in lowering ecological and carbon impacts becomes more pronounced. The findings suggest that scaling up REG alleviates environmental pressure and intensifies its positive effects over time. Additionally, (Li et al., 2023c), focused on the BRICS nations from 1990 to 2019, to assess the impact of renewable energy on CO_2 emissions. The study's results confirmed that renewable energy significantly mitigates CO_2 emissions within these rapidly industrializing countries, showcasing its potential to support sustainable development in emerging economies. Recent literature consistently demonstrates that renewable energy plays a pivotal role in reducing carbon emissions and environmental pressures. However, the degree of impact varies by region and economic context, indicating the relevance of suitable policies and investments. Considering the dominance of literature on the negative relationship between renewable energy and CO_2 emissions, the study hypothesizes that;

Hypothesis 2: Renewable energy negatively impacts CO_2 emissions.

2.4 Institutional quality (IQ), Green innovation, renewable energy and CO_2 emissions

Institutional quality reflects a nation's governance, legal framework, policy enforcement capabilities, and trust between the public and private sectors. High institutional quality fosters sustainable practices by ensuring that environmental regulations are enforced consistently and transparently. As (Bayar et al., 2021) argue, that countries with effective governance structures tend to see reduced CO_2 emissions since institutions can coordinate long-term environmental strategies effectively. Governance mechanisms such as corruption control, regulatory oversight, and policy coherence are particularly critical in emerging economies (Karim et al., 2022). These institutions act as gatekeepers, ensuring that businesses comply with environmental standards. Moreover, robust institutions promote green investments by offering investors security and reducing bureaucratic inefficiencies (Zhao et al., 2023). This stability encourages private-sector participation in emission reduction initiatives. In contrast, weak institutions create uncertainty, leading to underinvestment in GIN and REG, further worsening ecological footprints. Existing research has highlighted the link between the quality of institutions and environmental sustainability.

A study by Yuan et al. (2022) found that IQ plays a crucial role in moderating the effect of green innovation on CO_2 emissions. The study revealed that higher institutional quality amplifies the effectiveness of green innovation, leading to a more substantial reduction in CO2 emissions when institutional standards are strong. Also, (Bayar et al., 2021), conducted a co-integration analysis across 11 EU transition economies from 2000 to 2018, discovering varied impacts of IQ on CO_2 emissions. Specifically, stronger institutions were connected to lower CO_2 emissions in the Czech Republic, highlighting their environmental benefit. In contrast, in Latvia and Lithuania, institutional quality appeared to correlate positively with CO2 emissions, an indication that effective institutional contexts for mitigating emissions can differ significantly across countries. Similarly, (Amin et al., 2023), focused on South Asian economies, assessing the role of IQ in environmental sustainability from 1995 to 2020. The results depicted that IQ in these regions did not contribute positively to environmental outcomes; instead, it had a detrimental effect, suggesting that institutional inefficiencies may hinder effective carbon management.

In a study covering 25 African countries from 2000 to 2018, (Obobisa et al., 2022), investigated the role of institutional quality. The research found that IQ in these nations tended to exacerbate CO_2 emissions, indicating that stronger institutions did not necessarily lead to better environmental performance within this context. Conversely, (Karim et al., 2022), explored 30 Sub-Saharan African (SSA) countries between 2000 and 2021, focusing on various measures of IQ such as the rule of law, quality of regulations, and corruption index. The study confirmed that high IQ significantly reduced CO_2 emissions. This indicates that as institutions improve, environmental outcomes tend to get better, particularly in SSA. Again, (Salman et al., 2019), assessed the impact of IQ on economic and environmental metrics across East Asian countries from 1990 to 2016. The study concluded that IQ supports economic growth and influences carbon emissions. A unidirectional causality was identified, indicating that improvements in institutional quality can drive changes in carbon emissions in both the interim and long run.

Again, (Haldar and Sethi, 2021), expanded the analysis by examining 39 developing countries between 1995 and 2017. The study utilized a range of econometric methods to assess the connection between IQ, energy use, and CO_2 emissions. The findings revealed that IQ enhances the efficiency of energy use in mitigating carbon emissions. Furthermore, the study supported the EKC hypothesis, confirming that stronger institutions help stabilize and reduce emissions as economies grow. Also, (Jiang et al., 2022), focused on 57 countries along the Belt and Road Initiative (B&R) corridor using data from 1995 to 2018. The study demonstrated that improved institutional quality contributed to significant reductions in CO_2 emissions in the B&R nations, accenting the relevance of strong institutions in attaining ecological sustainability. The literature on environmental quality and carbon emissions highlights that while strong institutions generally facilitate emissions reductions, regional variations suggest that the context and nature of institutional frameworks are critical. Therefore, the study is based on these past theoretical underpinnings and hypothesizes that;

Hypothesis 3: Institutional quality moderates the effectiveness of green innovation and renewable energy in reducing CO_2 emissions

3 Methods and data

3.1 Data sourcing and variables

The study collected data from 30 emerging (E-30) (See Supplementary Table S1) nations identified as potential growth drivers in comparison to China and other advanced economies over the period 1990 to 2020. The countries considered were solely based on data availability in alignment with our study's objectives. Each variable—carbon dioxide emissions (CDE), renewable energy (REG), green innovation (GIN), environmental policy (POL), institutional quality (IQ), economic growth (GDP), and population growth (PON)—was chosen based on its relevance to the United Nations Sustainable Development Goals (SDGs), particularly Goals 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 9 (Industrial Innovation), and 13 (Climate Action). CDE is the primary dependent variable, representing environmental impact. REG is an independent variable that captures renewable energy development in emerging economies out of their total energy. Green innovation is also an independent variable capturing the technological advancements in the countries under study. Institutional quality is also adopted as an independent moderating variable that represents governance effectiveness and policy enforcement. Environmental policy signifies policies put in place to ensure adherence to environmental sustainability. Economic growth (GDP) and Population growth are added as control variables to account for socio-economic factors influencing emissions. These variables were selected because they collectively capture the key drivers of environmental sustainability in emerging economies and also align with the EKC, IDT, and institutional theoretical frameworks. CDE is the primary indicator of environmental impact, while REG and GIN represent technological and policy-driven solutions to mitigate emissions as used in many studies in the field (Akan et al., 2023; Chen et al., 2023; Naeem et al., 2023). IQ and POL were adopted following their role in various studies including (Obuobi et al., 2024; Maji et al., 2023; Xu et al., 2019), reflecting the institutional and regulatory frameworks necessary for the effective implementation of green initiatives. The variables, GDP and PON are adopted as control variables in tandem with the studies of (Androniceanu and Georgescu, 2023; Mohamed, 2023; Obuobi et al., 2022) to account for economic and demographic factors that influence emissions. All these variable selections are guided by past studies to determine their influence on CDE. This selection ensures a comprehensive analysis of the factors shaping environmental sustainability in emerging economies. Data were sourced from the WDI and the OECD databases. Data from these sources are verified and reliable, and are used by many studies. Table 1 provides a detailed summary of the variables, including their abbreviations, measurement units, and data sources. A descriptive analysis of the data is also presented in Table 2, which summarizes the mean, median, maximum, minimum, and standard deviation for each variable, providing a comprehensive overview of the dataset.

3.2 Study methodology structure

The process of methods for this research is illustrated in Figure 1. The process began with a cross-section dependency test (Breusch and Pesaran CD) to confirm that the variables were independent of any nuisance effects. Second, panel unit root tests (ADF, PP, and IPS) were conducted to evaluate the stationarity of the series. Following this, the Pedroni and Kao cointegration tests were employed to investigate the long-term relationships among the variables. In the third stage, three estimation methods—Ordinary Least Squares (OLS), Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS)—were utilized to analyze the impact of various determinants on greenhouse gas (GHG) emissions. The choice of OLS, FMOLS, and DOLS estimators is motivated by their complementary strengths in addressing the research objectives. OLS is a widely used method for its simplicity and ease of interpretation, making it a suitable baseline for initial analysis. However, OLS has limitations in handling endogeneity and serial correlation, which are common in

TABLE 1 Data and description.

Var.	Duration	Abb.	Measure	References
Carbon dioxide emissions	1990–2020	CDE	kt of CO2 equivalent	WDI (2023)
Renewable energy	1990–2020	REG	(% of total final energy consumption)	WDI (2023)
Green Innovation	1990–2020	GIN	Environmentally related technologies	WDI (2023)
Environmental policies	1990–2020	POL	Environmentally related tax	WDI (2023)
Institutional Quality	1990–2020	IQ	Government Effectiveness	
Economic Growth	1990–2020	GDP	Annual percentage % change	WDI (2023)
Population Growth	1990–2020	PON	Annual percentage % Change	WDI (2023)

TABLE 2 Descriptive statistics.

	CDE	REG	GIN	POL	IQ	GDP	POG
Mean	9.166	3.137	2.277	−0.286	−1.148	1.265	0.227
Median	8.294	3.238	2.680	0.178	−0.981	1.417	0.358
Maximum	13.013	4.458	4.238	1.421	0.140	2.507	1.807
Minimum	6.985	2.191	0.742	−3.507	−4.290	−3.387	−3.435
Std. Dev	1.896	0.581	0.856	1.064	0.906	0.798	0.820
Skewness	1.047	0.233	−0.507	−0.683	−1.228	−2.274	−1.970
Kurtosis	2.704	2.075	1.954	2.230	4.446	11.463	7.867
Jarque-Bera	26.836	6.439	12.729	14.771	48.715	553.795	235.257
Probability	0.000	0.040	0.002	0.001	0.000	0.000	0.000

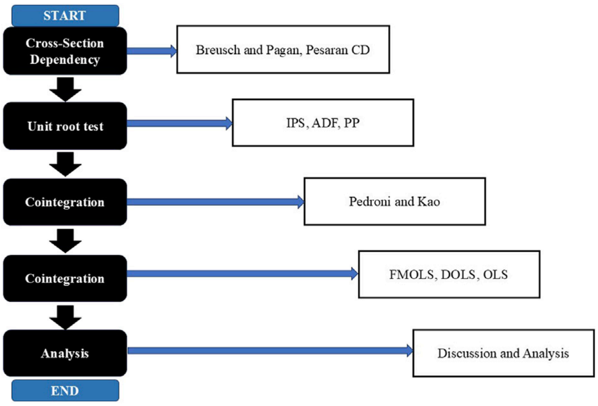

FIGURE 1
Methodological processes.

panel data. To address these issues, we employ FMOLS, which corrects for endogeneity and serial correlation, providing more reliable estimates in cointegrated systems. DOLS further enhances the robustness of our results by accounting for potential correlations between regressors, making it particularly effective for dynamic panel data analysis. By comparing the results from these three models, we ensure a comprehensive understanding of the relationships among the variables, capturing both short-term dynamics and long-term equilibrium effects. This multi-model approach allows us to validate the consistency of our findings and provides a more nuanced perspective on the determinants of CO_2 emissions in emerging economies.

3.3 Model specification

To achieve the objectives of the study, the study adopted an econometric model to produce results. The variables adopted were written in a function to serve as the basis for the model development. The variables used in developing the model are carbon dioxide emissions, renewable energy, environmental policy, institutional quality, economic growth, and population growth in the E-30 economies. Equation 1 depicts the function for further econometric model development.

$$CDE = f\,(REG, GIN, POL, IQ, GDP, PON) \qquad (1)$$

Where CDE represents carbon dioxide, while REG, GIN, POL, IQ, GDP, and PON denote renewable energy, green innovation, environmental policy, institutional quality, economic growth and population respectively. To standardize the data across the variables, the study converts the variables into their logarithm states to develop the econometric model in Equation 2.

$$LNCO2_{it} = \beta_0 + \beta_1 LNREG_{it} + \beta_2 LNGIN_{it} + \beta_3 LNPOL_{it} + \beta_4 LNIQ_{it} + \beta_5 \beta LNGDP_{it} + \beta_6 \beta LNPON_{it} + \varepsilon_{it} \qquad (2)$$

Where LN denotes the natural log, β_1-β_6 shows the coefficients. β_0 is the intercept. i and t are 1 and show the nations and the period, respectively. The ε_{it} is the stochastic error term and is considered to be serially not correlated.

3.4 Unit root test

For the econometric model to be valid, ensuring that all variables are stationary is essential. In this study, panel unit root tests were employed to assess data stationarity. Since working with both time series and cross-sectional data requires high-quality datasets, three prominent tests were applied: the Fisher-augmented Dickey-Fuller (ADF) test (Maddala and Wu, 1999), the IPS unit root test proposed by Im et al. (2003), and the Phillips-Perron test (Perron, 1990). These tests were chosen to confirm methodology validity. The ADF regression was estimated, and residuals for each panel cross-section were calculated as outlined in Equation 3

$$\Delta y = a_i + p_i y_{i,t-j} + \gamma_1 \bar{y}_{t-1} + \sum_{j}^{k} \gamma_{ij} \Delta \bar{y}_{i,t-j} + \sum_{j=0}^{k} \Delta \bar{y}_{i,t-j} + \varepsilon_{it} \qquad (3)$$

Where $\bar{y}_{t-1} = (\frac{1}{N})\sum_{i=1}^{N} y_{i,t-1}, \Delta\bar{y}_t = (\frac{1}{N})\sum_{i=1}^{N} y_{it}$ and t_i (N, T) is the t-stats of the estimates, and P′ is the individual ADF statistics

3.5 Cross-section dependency test

In models of this type, addressing cross-section dependency is crucial. In such an analysis, challenges arise if the face of smaller cross-sectional units (N) over the period (T), leads to potential cross-sectional dependence issues. This imbalance, known as the "large N, small T" problem, limits accurate estimation. To detect cross-sectional dependence, the study applied the Pesaran CD test, with its formulation presented in Equation 4.

$$CD = \frac{NT}{N-1} \frac{\sum_{i=1}^{N} \sum_{t=1}^{T} \widehat{P_{it}}}{\sum_{i=1}^{N} \sum_{t=1}^{T} \widehat{P_{it}^2}} \qquad (4)$$

3.6 Cointegration test

The next phase involves examining the co-integration relationships among the variables. Since every becomes stationary after differencing, the Pedroni and Kao (Pedroni, 1999) tests are considered suitable for this analysis. Pedroni's approach is particularly advantageous as it accommodates multiple explanatory variables, making it well-suited for the framework of this study. This method assesses whether a long-term equilibrium relationship exists among the variables, even if they may exhibit short-term deviations. The general structure of the co-integration model used in this analysis is outlined in Equation 5.

$$\mu_{it} = p_i \mu_{it} - \mu_{it} \qquad (5)$$

Here, i = 1, t = 1.

3.7 Regression and long run analysis

To gain deeper insights, this study compares three different estimation methods: Ordinary Least Squares (OLS), Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least

Squares (DOLS). While OLS is a widely used technique, it has faced criticism for its simplicity and its limitations in yielding reliable results, particularly in the presence of complex relationships among variables. On the other hand, FMOLS, originally established by Pedroni (Pedroni, 2000), is a residual-based approach that provides more reliable estimates in cases involving co-integrated variables. This method is particularly reliable when dealing with smaller sample sizes, as it effectively addresses issues of endogeneity and serial correlation that may arise in the data (Hamit-Haggar, 2012). Additionally, DOLS, introduced by (Stock and Watson, 1993), is designed to produce even more reliable results than FMOLS. It does so by correcting for correlations between the regressors, which can lead to more accurate estimations (Kao and Chiang, 2000). Consequently, this study employs all three models to compare their outcomes, focusing on how each method represents the interactions among the variables under investigation. By analyzing the results from OLS, FMOLS, and DOLS, the study aims to identify the strengths and limitations of each approach. Their general forms are shown in Equations 6, 7 as follows

$$\beta FMOLS = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\sum_{t=1}^{T}(A_{it} - bar\ A_i)\right)^2\right]^{-1} \times \sum_{t-1}^{T}(A_{it} - bar\ A_i)^2 barY_{it} - Tbar\Delta_{e\mu} \quad (6)$$

$$\beta DOLS = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\sum_{t=1}^{T}(A_{it}A'_{it})\right)^2\right]^{-1}\sum_{i=1}^{N}\left(\sum_{t-1}^{T}(A_{it}Y_{it})\right) \quad (7)$$

Here Y is the endogenous variable and A denotes the exogenous variables

4 Study results and discussion

4.1 Data descriptives

The data descriptives are presented in Table 2. From the table, the mean values for carbon dioxide emissions (CDE), renewable energy generation (REG), green innovation (GIN), environmental policy (POL), institutional quality (IQ), economic growth (GDP), and population growth (POG) are 9.166, 3.137, 2.277, −0.286, −1.148, 1.265, and 0.227, respectively. These averages reflect the general trends observed across the selected emerging economies over the study period. Regarding variability, CDE exhibited the highest standard deviation at 1.896, suggesting more significant fluctuations in emissions across countries. In contrast, REG recorded the lowest standard deviation at 0.581, indicating more consistency in renewable energy output. This variation highlights the uneven distribution of emissions and renewable energy adoption among the economies under investigation. The skewness of the variables reveals that all variables are negatively skewed, except for CDE (1.047) and REG (0.233), which exhibit positive skewness. Positive skewness in CDE suggests that a few countries have exceptionally high emissions compared to the rest, while the positive skewness in REG indicates that a small number of countries lead in renewable energy generation. Conversely, the left skew in other variables suggests that most countries cluster around higher values, with fewer countries at the lower end of the distribution.

4.2 Results of cross-section dependency

Table 3 presents the findings from the Pesaran CD tests, which were conducted to assess the presence of cross-sectional dependency among the variables. The null hypothesis for these tests asserts that there is "no cross-section dependency," with p-values serving as the metric for evaluation. A p-value of less than 5% would allow for the rejection of the null hypothesis (H0), indicating potential cross-sectional dependency issues within the variables. In this study, the results revealed a p-value of 0.998 for the Breusch-Pagan LM test and 0.869 for the Pesaran CD test, both of which exceed the 5% threshold for rejection. Consequently, the null hypothesis cannot be rejected, leading to the conclusion that there is no significant cross-sectional dependence among the variables under consideration. This finding is crucial as it validates the appropriateness of the dataset for further econometric analysis, ensuring that the assumptions underlying the chosen econometric techniques are met.

4.3 Results of unit roots

According to the results presented in Table 4, each variable was examined both at its levels and at its first differences to determine their stationarity. The IPS test revealed that only POL, GDP, and POG were significant at the levels, while all variables achieved significance at the first difference. In the case of the ADF test, only GIN, POL, GDP, and POG were significant at the levels, but again, all variables were significant at the first difference. Similarly, the PP test indicated that all variables were significant at the first difference. All three tests met the study's criteria, confirming that the variables are stationary at the 1% significance level. These results pave the way for conducting the regression analysis as part of the study.

4.4 Cointegration test

The outcomes of both the Pedroni and Kao tests are detailed in Table 5, providing a clear representation of the evidence supporting these long-term relationships. In the Pedroni analysis of both within and between dimensions, 6 out of the 11 tests indicated significant support for co-integration. This suggests that all selected emerging economies (E-30) are co-integrated. Consequently, it can be inferred that there exists a stable long-run relationship among all variables analyzed. The Kao panel co-integration technique corroborates those of the Pedroni test. This comprehensive approach to co-integration analysis strengthens the reliability of the study's findings and underscores the interconnectedness of the examined variables across the selected emerging economies.

TABLE 3 Cross-section dependency. H_0: Cross-section dependency does not exist.

Test	Statistic	Prob
Breusch-Pagan LM	60.866	0.998
Pesaran CD	−0.164	0.869

TABLE 4 Panel unit root test.

	IPS				ADF				PP			
	Lev.		1st diff.		Lev.		1st diff.		Lev.		1st diff.	
	Stat	P value	Stat	P value	Stat	P value	Stat	P value	Stat	P value	Stat	P value
CDE	1.770	0.962	−16.112	0.000	68.920	0.201	361.919	0.000	65.003	0.307	582.301	0.000
REG	3.078	0.999	−15.013	0.000	36.548	0.993	330.700	0.000	69.474	0.189	598.620	0.000
GIN	−0.610	0.271	−16.575	0.000	81.080	0.000	315.656	0.000	105.906	0.000	490.796	0.000
POL	−23.900	0.000	−41.787	0.000	90.517	0.004	373.075	0.000	80.929	0.025	621.198	0.000
IQ	2.121	0.983	−6.538	0.000	2.919	0.983	59.526	0.000	7.218	0.705	119.427	0.000
GDP	−4.284	0.000	−14.583	0.000	132.078	0.000	335.681	0.000	336.296	0.000	1,229.585	0.000
PONG	−5.498	0.000	−12.502	0.000	165.237	0.000	288.584	0.000	133.680	0.000	272.610	0.000

Note: ***1%, **5%, and *10%. Reject null at 10%.

TABLE 5 Pedroni and Kao residual cointegration test.

Kao				
Test	t-Statistic		Prob.	
ADF	−0.810		0.021	
Pedroni				
Alternative hypothesis: common AR coefs. (within-dimension)				
			Weighted	
	Statistic	Prob	Statistic	Prob
Panel v-Statistic	−21.536	1.000	−2.361	0.991
Panel rho-Statistic	−0.226	0.411	−0.065	0.474
Panel PP-Statistic	−2.682	0.004	−2.275	0.012
Panel ADF-Statistic	−1.367	0.086	−1.393	0.082
Alternative hypothesis: individual AR coefs. (between-dimension)				
	Statistic		Prob	
Group rho-Statistic	0.554		0.710	
Group PP-Statistic	−3.515		0.000	
Group ADF-Statistic	−1.611		0.054	

Note: ***1%, and **5%. *10%. Reject null at 10%.

4.5 The outcomes of OLS, FMOLS, and DOLS estimators

The results obtained from the FMOLS, DOLS, and OLS models as presented in Table 6 provide valuable insights into the relationship between various determinants—such as renewable energy, green innovation, environmental policy, institutional quality, economic growth, and population—and carbon dioxide emissions in emerging economies.

In the FMOLS results, the effects or coefficients of renewable energy, green innovation, environmental policy, institutional quality, economic growth, and population on carbon dioxide emissions are (−0.300), (0.360), (0.150), (0.085), (−0.045) and (0.064) respectively. The *R*-squared is 0.998. With an *R*-squared value of 0.998, the FMOLS model indicates that about 99.8% of the variability in carbon dioxide emissions can be explained by the selected variables. The negative coefficient for renewable energy suggests that an increase in renewable energy use is associated with a reduction in carbon emissions, which aligns with sustainability goals. This corresponds with the study of (Li et al., 2023b). In contrast, green innovation positively correlates with emissions, implying that certain innovations may initially increase emissions, possibly due to higher production processes before achieving efficiency gains. Environmental policy and institutional quality also positively influence emissions, suggesting that effective policies and institutions are critical in managing environmental impacts. This confirms the institutional theory that suggests that without strong environmental frameworks, governments' efforts towards sustainable development will not be fruitful. This finding contradicts the studies of Zhao et al. (2023) and Obuobi et al. (2024). Economic growth's negative coefficient indicates a complex relationship where growth may lead to reduced emissions, potentially due to cleaner technologies or improved efficiency. The positive effect of population suggests that higher populations may contribute to increased emissions, highlighting a critical challenge for emerging economies.

In the DOLS results, the effects or coefficients of renewable energy, green innovation, environmental policy, institutional quality, economic growth, and population on CO_2 emissions are (7.141), (−2.675), (2.383), (0.327), (−3.153) and (−1.882) respectively. The *R*-squared is 0.999. The *R*-squared value for the DOLS model is 0.999, indicating an even stronger explanatory power than FMOLS. The large positive coefficient for renewable energy may reflect significant investment or technological advancements that lead to substantial emissions increases during the transition to renewable sources. Conversely, the negative

TABLE 6 Regression results of FMOLS, DOLS, and OLS.

Variable	FMOLS			DOLS			OLS		
	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.
REG	−0.300	−3.319	0.001	7.141	14.347	0.000	−2.420	−12.698	0.000
GIN	0.360	3.144	0.002	−2.675	−4.481	0.007	−0.754	−6.927	0.000
POL	0.150	2.246	0.027	2.383	5.631	0.002	0.507	5.758	0.000
IQ	0.085	0.751	0.045	0.327	1.041	0.035	−0.497	−4.836	0.000
GDP	−0.045	−0.352	0.726	−3.153	−3.582	0.016	−0.072	−0.702	0.484
POP	0.064	1.619	0.109	1.882	−3.817	0.012	0.549	4.085	0.000
C							18.014	30.695	0.000
R^2	0.997			0.999			0.773		
Adj. R^2	0.996			0.989			0.763		

Note: ***1%, **5%, and *10%. Reject at 10%.

coefficient for green innovation suggests that it can effectively reduce emissions, aligning with the idea that innovations lead to more sustainable practices. These findings support the IDT that gives basis to this research. Moreover, this finding corroborates that of Obobisa et al. (2022). Environmental policy also shows a positive relationship, suggesting that while policies are essential, they may require time to fully implement and realize their impact. Economic growth's substantial negative coefficient indicates that robust economic growth can correlate with significant emission reductions, possibly due to structural changes in the economy towards greener practices. It highlights the EKC theory which indicates that at some point economic growth leads to environmental pollution reduction because the government invests in green initiatives. The population's positive coefficient further emphasizes the connection between demographic factors and emissions.

For the OLS outcome, the effects or coefficients of renewable energy, green innovation, environmental policy, institutional quality, economic growth, and population on CO_2 emissions are (−2.42), (−0.754), (0.507), (−0.497), (−0.072) and (0.549) respectively. The *R*-squared is 0.773. With an R-squared of 0.773, this model explains only 77.3% of the variation in emissions, indicating a weaker fit compared to the FMOLS and DOLS models. The negative coefficient for renewable energy reaffirms its role in reducing emissions, while green innovation also appears to contribute positively, albeit at a lower magnitude than in the FMOLS results. Environmental policy shows a positive effect on emissions, which could indicate inefficiencies in policy implementation or enforcement. The institutional quality's negative coefficient may suggest that better institutions help mitigate emissions. Economic growth's near-zero coefficient and insignificant p-value suggest that in the context of the OLS model, growth does not significantly impact emissions. The population coefficient is notably positive, reaffirming concerns about the environmental impact of rising populations.

When comparing the three models, both FMOLS and DOLS provide stronger *R*-squared values (0.998 and 0.999, respectively) compared to OLS (0.773), suggesting that the latter fails to capture the relationships adequately. The DOLS model offers the best explanatory power and provides coefficients that align with theoretical expectations regarding renewable energy and green innovation. The FMOLS model, while slightly less robust than DOLS, also yields insightful results, especially regarding the relationships among the variables. The large coefficients in the DOLS model may indicate a more dynamic relationship that accounts for adjustments over time, which could be critical in emerging economies undergoing rapid changes. The findings emphasize the relevance of investing in clean energy and green innovation to mitigate carbon emissions. Policymakers should consider the complex interactions among these determinants, focusing on implementing effective environmental policies and improving institutional quality to support sustainable economic growth. The positive correlation between population and emissions indicates the need for strategies addressing urbanization and population growth, particularly in developing regions. Overall, while both FMOLS and DOLS models show promise, DOLS may be the preferred method for this research, as it provides a more comprehensive understanding of the dynamic relationships between the variables.

5 Conclusion and policy implications

5.1 Conclusion

This study examined the impact of various determinants—namely renewable energy, green innovation, environmental policy, institutional quality, economic growth, and population—on carbon dioxide emissions in 30 emerging economies from 1990 to 2020. The analysis utilized three econometric models: The FMOLS, DOLS, and OLS, with all showing high explanatory power at 97.7%, 99.9%, and 77.3% respectively. The findings indicate that REG has a negative effect with CDE in FMOLs and OLS, indicating the crucial role in reducing carbon emissions, and supporting the shift towards more sustainable energy sources. However, the DOLS results proved otherwise. Again, Green innovation had a negative relationship with CDE in the DOLS and OLS model, highlighting its potential to drive emissions reductions through advanced technologies and practices. The results from FMOLS found otherwise. Institutional quality emerges as a critical moderating factor, amplifying the effectiveness of green initiatives when governance frameworks are strong. In the FMOLS and DOLS results, the study found that IQ and POL have a positive effect on CDE, indicating that they escalate carbon emissions. This suggests that effective implementation and governance are vital for achieving intended environmental outcomes. The DOLS results found a significant negative relationship between GDP and CDE indicating that economic growth in emerging countries has reduced carbon emissions. However, the other models had insignificant impacts. Lastly, the positive association between population growth and emissions (FMOLS and OLS) raises critical concerns for policymakers. The DOLS found a negative relationship between the two. Based on these results, we conclude that a holistic approach integrating renewable energy, green innovation, and institutional strengthening is essential for achieving environmental sustainability in emerging economies. These findings underscore the complexities of sustainable development in emerging economies. While renewable energy and green innovation can drive emissions reductions, their effectiveness varies across models, highlighting the need for targeted policies. Strong governance and environmental policies alone may not guarantee sustainability unless properly enforced. Economic growth's mixed impact on emissions suggests that green growth strategies must be prioritized. Lastly, the positive link between population growth and emissions signals the urgency of balancing development with environmental responsibility.

5.2 Policy implications

The findings of this study offer several actionable insights for policymakers and stakeholders in emerging economies. It provides actionable insight into investments in renewable energy infrastructure, green innovation development through research and development (R&D), strengthening institutional frameworks and environmental policies, as well as addressing the challenges posed by population growth and urbanization. To achieve these, the following have been elaborated to policymakers to guide policy design and implementation.

First of all, the study found a significant relationship between renewable energy and carbon emissions. Therefore, it is admonished that policymakers prioritize investments in clean energy infrastructure to significantly diminish reliance on fossil fuels and mitigate carbon emissions. This can be achieved by providing financial incentives such as subsidies, grants, and low-interest loans for renewable energy projects, encouraging private investment. Additionally, they can focus on establishing regulatory frameworks that facilitate the growth of renewable energy sectors, including streamlined permitting processes and policies that require a certain percentage of energy to come from renewable sources. Moreover, they must consider upgrading electricity grids to accommodate renewable energy sources can improve energy efficiency and reliability. This involves investing in smart grid technologies that enhance the management and distribution of energy generated from renewable sources. Public awareness campaigns are also vital to educate the public about the benefits of renewable energy, creating a supportive environment for transitioning to cleaner energy sources.

Second, the significant relationship between green technological innovation and carbon emissions is a call to policymakers to encourage innovation in green technologies which is essential for sustainable development. Based on this finding, policymakers can take several steps to stimulate this sector, including supporting research and development (R&D) in green technologies by allocating funding for clean energy solutions, energy efficiency improvements, and sustainable agricultural practices. This can be done by collaborating with universities, research institutions, and private sector innovators to enhance technological advancements. Moreover, when tax breaks or grants are provided for businesses that develop or adopt innovative green technologies, it can incentivize their efforts. Again, we admonish governments to establish innovation hubs or incubators. These can foster collaboration between startups and established firms focused on sustainability. In addition to these, they must also develop educational programs that focus on sustainability and green technology to build a skilled workforce that is equipped to support the transition to a greener economy.

Third, the study established the significant role played by institutional quality and environmental policies in mitigating carbon emissions. This indicates that effective environmental policies and governance are crucial for achieving emissions reduction targets. Therefore, we encourage policymakers to enhance their governance frameworks by improving regulatory frameworks that establish comprehensive, enforceable, and adaptable environmental regulations. To achieve this, policymakers must set clear emissions reduction targets and monitor compliance. Also, they must promote transparency in environmental governance by making data on emissions and environmental impacts publicly accessible fostering accountability and building trust between the government and citizens. In addition to these, governments must involve local communities, businesses, and non-governmental organizations in the policymaking process to ensure that diverse perspectives are considered. Also, public consultations and stakeholder engagement initiatives must be brought on board to help create policies that are more effective and widely accepted. Another important aspect of ensuring workable policies is to provide training and resources to personnel involved in environmental management to enhance their effectiveness.

Finally, as population growth and urbanization present significant challenges to environmental sustainability in the study, we encourage policymakers to adopt integrated strategies. This is in line with the environmental Kuznets Curve as emerging economies are experiencing environmental pollution at their initial growth stage. To ensure these countries grow in green, we admonish governments of these nations to develop comprehensive urban plans that prioritize sustainability and can guide the growth of cities while minimizing environmental impact. These actions include zoning laws that encourage mixed-use development, reducing urban sprawl, and preserving green spaces. In that scope, enhancing public transportation infrastructure can reduce reliance on personal vehicles, thus lowering emissions. Again, we advise policymakers to focus on expanding and improving the efficiency of public transit systems to encourage their use. This must also be accompanied by promoting energy-efficient housing through the encouragement of energy-efficient buildings to help reduce carbon footprints. On the problem of population growth in emerging economies, we encourage the implementation of educational campaigns that highlight the environmental impacts of population growth to empower communities to adopt sustainable behaviors. This includes promoting family planning, resource conservation, and community engagement in sustainability initiatives. By implementing these policies, emerging economies can effectively address the challenges posed by carbon emissions while promoting sustainable development and economic growth.

5.3 Limitations and future direction

The study recorded a few limitations that may affect the results and pave the way for future research. First, the study is based on data from 30 emerging economies, which may vary in quality and completeness. Disparities in data collection methods, reporting standards, and timeframes across countries could introduce bias or inconsistencies in the analysis. Moreover, certain variables might not be adequately captured, leading to the potential underrepresentation of critical factors influencing carbon emissions. Second, while the study employed multiple econometric models (FMOLS, DOLS, and OLS), the complexity of the relationships among the variables may not be fully captured. The models assume linear relationships, which may oversimplify the interactions between determinants. Future research could explore a broader range of determinants affecting carbon emissions, including technological advancements, energy efficiency measures, and sector-specific policies. Incorporating variables such as international trade patterns and investment in green technologies could provide more insights into determinants of CO_2 emissions in emerging economies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JG: Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

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

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1525281/full#supplementary-material

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