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Evaluating the role of renewable energy and government consumption in reducing CO_2 emissions: A dynamic panel data analysis

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ABSTRACT

Reducing CO_2 emissions poses a critical challenge for rapidly industrializing lower-middle-income countries (LMICs), where economic expansion pushes enhanced energy consumption, industrial activity, and transportation emissions. While previous research has separately examined the roles of renewable energy adoption and government spending in mitigating emissions, this study uniquely investigates their combined and interactive effects on CO_2 emissions in LMICs, providing novel empirical insights through dynamic analysis. This research employs panel data from 26 LMICs spanning 2002 to 2022, utilizing fixed-effects, random-effects, and generalized method of moments (GMM) approaches to address endogeneity, autocorrelation, and unobserved heterogeneity. The robust GMM estimators, handling these issues effectively, ensure reliable and complete causal inferences. The findings from the preferred GMM model indicate that a 1 % increase in renewable energy consumption results in a 0.025 % reduction in CO_2 emissions, but a 1 % rise in government expenditure contributes to a 0.0531 % decrease, when spending is environmentally aligned. However, the interaction term between renewable energy and government consumption demonstrates a small but significant positive effect, indicating that poorly targeted fiscal spending may dilute the environmental benefits of renewables. GDP growth and energy use dramatically rise emissions, supporting the Environmental Kuznets Curve (EKC) hypothesis, while urbanization and education show mixed effects. These results underscore the necessity of integrating renewable energy expansion with strategic government fiscal interventions to promote sustainable emission reductions. The study adds to the body of knowledge on sustainable development literature by elucidating the complex interplay between fiscal policy and renewable energy adoption. We recommend that policymakers in LMICs prioritize green-aligned spending and phase out fossil incentives to maximize synergies, fostering scalable models for global climate goals.

1. Introduction

In today's world, tackling carbon dioxide (CO_2) emissions represents a vital priority, especially in low- and middle-income countries (LMICs). These nations are experiencing swift industrial expansion, rising populations, and urban development, which intensify emissions from sources like fossil fuel use, transport systems, and manufacturing processes (Bélaïd and Youssef, 2017; Muhammad and Long, 2021). By

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2024, worldwide CO_2 emissions linked to energy production hit a record 37.8 gigatonnes (Gt), marking a 0.8 % rise from the year before and elevating atmospheric CO_2 levels to 422.5 parts per million (ppm) about 50 % higher than during the pre-industrial era (International Energy Agency, 2025). This concerning pattern underscores ongoing research on the need for shifting toward renewable energy sources and well-planned public spending strategies as key approaches for curbing emissions and promoting long-term economic progress, particularly in rapidly evolving LMICs (Azam et al., 2021; Fig. 1).

Renewable energy has appeared as a cornerstone of universal efforts to reduce emissions, with recent studies confirming its significant impact in rapidly expanding economies (Agbortoko Egbe et al., 2024; Wang et al., 2023). In 2024, global renewable energy capacity increased by 585 gigawatts (GW), a 15.1 % rise from the previous year, with solar power accounting for over three-quarters of new additions (International Energy Agency, 2025). However, this progress remains uneven, as China, the U.S.A, and the European Union (Bélaïd and Youssef, 2017) accounted for 83.6 % of new capacity, leaving many LMICs lagging. Evidence from countries such as China, India, and several sub-Saharan African nations demonstrates that renewable energy adoption can reduce CO_2 emissions by 0.12 % to 0.25 % per 1 % increase in its use (Nasrullah et al., 2023; Wang et al., 2023). Despite this potential, the persistence of fossil fuel subsidies reaching USD 1.1 trillion globally in 2023 highlights the need for complementary policies to curb fossil fuel reliance and incentivize cleaner alternatives (Organization for Economic Co-operation and Development, 2024).

At the same time, public spending can enhance efforts to cut emissions if it is thoughtfully coordinated with ecological goals. This can be achieved by funding innovative eco-friendly technologies, implementing strict environmental rules, and building infrastructure that withstands climate challenges (Halkos and Paizanos, 2013; Oh, 2023). Global agreements like the Kyoto Protocol and the Paris Agreement have highlighted the value of combining shifts to renewable energy with financial strategies to meet broader aims for sustainable progress (Alola et al., 2019; Agbortoko Egbe et al., 2024). That said, in LMICs, these approaches often face hurdles due to tight financial resources, inadequate governance structures, and conflicting needs for growth, which prompts doubts about how well they work alone or together in controlling emissions (Furkan et al., 2023).

While prior studies have explored the independent roles of renewable energy and government expenditure in reducing emissions, few studies have examined their interactive effects, particularly in the fiscal and developmental context of LMICs (Alola et al., 2019; Shahsavar et al., 2020). Many prior analyses have focused on high-income countries or treated these variables in isolation, limiting their relevance to nations facing distinct budgetary and infrastructural challenges (Haldar and Sethi, 2021; Ehigiamusoe and Dogan, 2022). This gap is significant, as the synergy or potential trade-offs between renewable energy adoption and government spending remain underexplored in LMICs, where such dynamics are critical for balancing economic growth with environmental sustainability (Halkos and Paizanos, 2013). Existing studies typically (i) analyze renewables or public spending in isolation, (ii) emphasize OECD/high-income samples, or (iii) rely on static specifications that understate emissions persistence and policy endogeneity. By contrast, we: (1) focus on LMICs where budget constraints, fossil-fuel subsidies, and grid frictions shape policy trade-offs; (2) estimate both main effects and the interaction RE $\times$ GC, allowing fiscal policy to amplify or attenuate the mitigation from RE; and (3) use dynamic System-GMM, addressing endogeneity, autocorrelation, and unobserved heterogeneity. This design lets us test a concrete mechanism: whether non-green GC can erode RE's emissions gains, versus green-aligned GC that reinforces them.

This research fills these research voids by examining both the standalone and combined influences of renewable energy consumption and government expenditure on CO_2 emissions across 26 low- and middle-income countries (LMICs) from 2002 to 2022. By applying advanced panel data methods such as fixed-effects models, random-effects models, and generalized method of moments (GMM) approaches the study effectively handles issues like endogeneity, autocorrelation, and unobserved heterogeneity among the countries. Additionally, it assesses how major economic variables, including GDP expansion, overall energy consumption, spending on education, urban expansion, and openness to trade, shape patterns in emissions. The analysis also examines the Environmental Kuznets Curve (EKC) theory to determine if increasing income levels ultimately result in better environmental outcomes within LMICs.

These variables are included as they represent the core drivers of environmental quality in developing economies. Renewable energy directly displaces fossil fuels, while government expenditure can either fund green transitions or support carbon-intensive growth. GDP growth

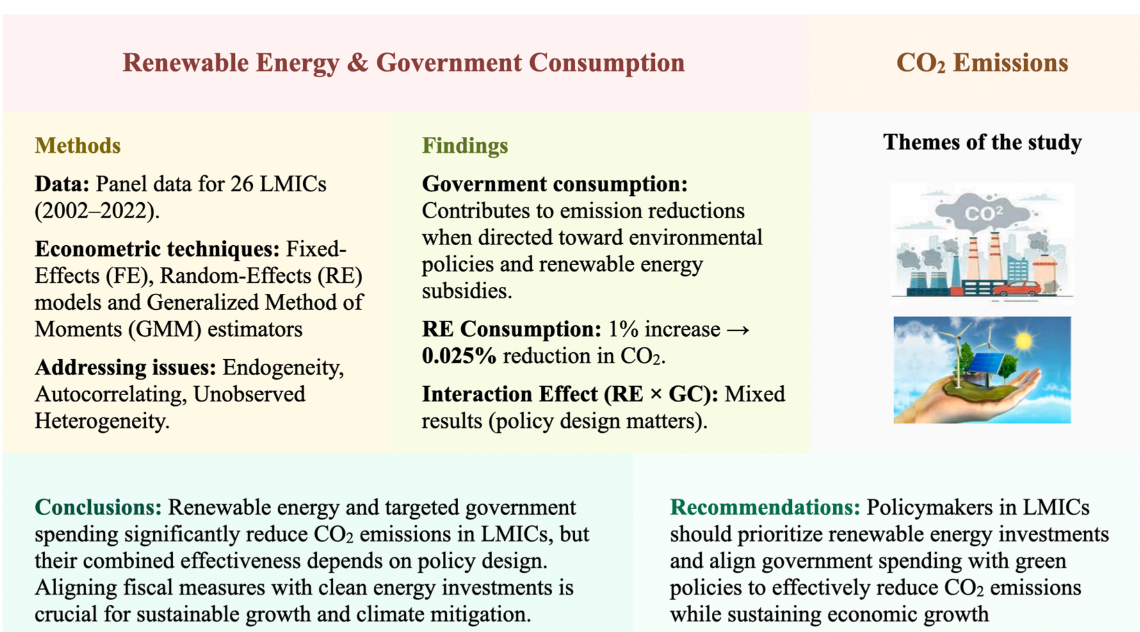

Fig. 1. Graphical presentation of the abstract.

and energy use are central to the EKC framework, capturing the scale of economic activity, while education, urbanization, and trade openness serve as control variables, reflecting social development, structural economic shifts, and technological diffusion that shape national emission trajectories. Over the study period, the average CO_2 emissions in the included LMICs were 1.973 million metric tons per capita, renewable energy consumption averaged 34.981 % of total final energy use, and government consumption averaged 13.2 % of GDP (WDI, 2025).

By integrating these variables into a comprehensive analytical model, this research contributes to the environmental economics literature and offers actionable evidence for policymakers in LMICs. This paper contributes in three ways. First, it centers on LMICs, where fiscal constraints and energy transitions make the RE–GC nexus uniquely policy relevant, whereas most prior evidence is drawn from high income settings or treats RE and GC separately. Second, we estimate both standalone and interactive effects (RE × GC) within a System GMM framework that explicitly tackles dynamics and endogeneity. Third, we uncover that RE's mitigation effect can be diluted by non green GC, directly informing the design of coherent fiscal–energy packages (e.g., aligning subsidies, public investment, and regulatory spending with RE deployment). The findings are particularly relevant for designing fiscal strategies that balance economic expansion with ecological stewardship, providing scalable solutions for emissions reduction in developing contexts. The study also holds broader significance for international climate policy, highlighting the importance of aligning renewable energy investments with targeted government spending to achieve sustainable development goals

We examine the standalone and interactive impacts of RE and GC on CO_2 across 26 LMICs (2002–2022) using panel econometric methods (FE/RE) and a dynamic System-GMM specification that addresses endogeneity, autocorrelation, and unobserved heterogeneity. Preview of findings, we find that higher RE is associated with lower CO_2; GC reduces CO_2 when environmentally aligned; the RE × GC term is small but positive, indicating that poorly targeted spending can dilute RE's gains; while GDP and energy use exert upward pressure on emissions, consistent with LMICs being on the upward EKC phase. By quantifying an actionable interaction channel (RE × GC) in LMICs within a dynamic framework, the paper informs both fiscal composition and energy-transition sequencing for future research and policy design. Section 2 reviews the literature; Section 3 describes data and methods; Section 4 reports results and discussions; Section 5 conclusion and policy implications

2. Literature review

This section reviews the theoretical framework, existing literature, and formulates testable hypotheses based on empirical evidence and theoretical foundations. It critically synthesizes key studies, evaluating their provenance, methodology, objectivity, persuasiveness, and value to highlight strengths, limitations, and inconsistencies in the field.

2.1. Theoretical framework

This study is grounded in an integrated set of complementary theories that explain the interactions among economic growth, government consumption, renewable energy adoption, and CO_2 emissions, in lower-middle-income countries (LMICs).

At its core is the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between economic growth and environmental degradation: emissions initially rise during industrialization but decline after a certain income threshold due to technological advancements, stricter regulations, and shifts to cleaner energy (Grossman and Krueger, 1995; Panayotou, 1997). This framework is especially relevant for LMICs, where rapid GDP growth often exacerbates emissions through increased energy demand, but eventually decoupling can occur via policy interventions. Complementing the EKC is the Energy Transition Theory, which emphasizes the gradual shift from fossil fuels to renewables as a means to decouple economic growth from carbon emissions, driven by technological innovation and policy support (Sovacool, 2016; IPCC, 2023). This theory underscores how renewable energy can displace fossil fuels, reduce emissions while sustain the development.

Additionally, Fiscal Environmentalism Theory highlights government expenditure's dual role: it can mitigate emissions through "green spending" on renewable infrastructure and regulations or exacerbate them via subsidies for carbon-intensive sectors (Halkos and Paizanos, 2013; Abd El-Aal, 2024; Yuan et al., 2025). This integrates with the Decoupling Hypothesis, which argues that targeted fiscal policies and renewable adoption can separate economic growth from environmental harm (IPCC, 2023). These theories are interconnected, the EKC provides the macroeconomic arc, Energy Transition Theory explains the role of renewables and energy use, and Fiscal Environmentalism addresses government consumption's moderating effects.

Control variables like education expenditure (linked to human capital theory; Schultz, 1961), urbanization (urban environmental transition theory; Marcotullio, 2012), and trade openness (pollution haven/halo hypotheses; Copeland, 2008; Zugravu-Soilita, 2018) are incorporated to capture contextual influences. This integrated framework guides the hypotheses, emphasizing the need for empirical testing in LMICs where institutional weaknesses may alter theoretical predictions, and supports the study's focus on interactive effects between renewables and government spending.

2.2. Existing studies

The growing danger posed by climate change has sparked in-depth investigations into the factors influencing CO_2 emissions, with a special focus on fast-developing lower-middle-income countries (LMICs). Scholars have thoroughly explored the connections between CO_2 levels and various influences, such as renewable energy usage, public spending, economic expansion, overall energy demand, educational investments, urban growth, and international trade involvement. Despite this, results are often inconsistent, particularly in the context of LMICs. The following subsections critically evaluate key studies on each variable, assessing their provenance, methodology, objectivity, persuasiveness, and value.

2.2.1. Renewable energy consumption and CO_2 emissions

The relationship between renewable energy adoption and CO_2 emissions reduction is supported by energy transition theory (Sovacool, 2016), which describes shifts from fossil fuels to cleaner sources via cost-reducing technologies and accessibility-enhancing policies. This aligns with the decoupling hypothesis (IPCC, 2023), positing renewables break growth-emissions links by substituting low-carbon alternatives.

Global evidence shows an inverse relationship: a 1 % rise in renewables cuts emissions by 0.5–1.25 % in energy-dependent nations (Huang et al., 2021; Szetela et al., 2022), with 0.18 % reductions in moderate-income countries (Majewski et al., 2022). LMIC patterns are reinforced by Ben Jebli et al. (2020), Ehigiamusoe and Dogan (2022), and Nathaniel and Iheonu (2019). Regionally, Sub-Saharan Africa sees 0.12–0.25 % cuts per 1 % increase (Wang et al., 2023), and Asian LMICs benefit from solar/wind adoption (Nasrullah et al., 2023). Variations include long-run emissions from both energy types in Sub-Saharan Africa (Adams and Nsiah, 2019), stronger negative correlations in developed nations (Agbortoko Egbe et al., 2024), and LMIC challenges like intermittency and costs (Haldar and Sethi, 2021; Behera et al., 2024a), with initial infrastructure potentially raising emissions (Bélaïd and Youssef, 2017).

Critically evaluating these studies: Sovacool (2016) and IPCC (2023) offer strong provenance as policy experts with global data (high value for applicability), while methodologies like panel data and GMM in Wang et al. (2023) and Nasrullah et al. (2023) address endogeneity effectively, though smaller samples in Adams and Nsiah (2019) limit generalizability. Objectivity is even-handed in Bélaïd and Youssef (2017) by noting short-term increases, with high persuasiveness in quantitative results (e.g., 0.12–0.25 % reductions) but weaker qualitative claims. These contribute to renewables' role but directly gap on fiscal policy interactions, underexploring synergies in LMICs. Based on this foundation, we hypothesize:

***H1:** Increased renewable energy consumption will significantly reduce CO_2 emissions.*

2.2.2. Government consumption and CO_2 emissions

Government expenditure influences CO_2 emissions via fiscal environmentalism (Halkos and Paizanos, 2013), with green spending on renewables, efficiency, and regulations lowering emissions (Oh, 2023; Wan et al., 2022), while growth-first policies on subsidies and expansion exacerbate them (Abd El-Aal, 2024; Hubacek et al., 2017).

Empirical findings are mixed: globally, it accounts for 10 % of emissions (Hertwich and Peters, 2009), with targeted spending reducing intensity in Pakistan (Fatima et al., 2021) and via 20 % sustainability allocations (Oh, 2023). Untargeted policies raise emissions in LMICs prioritizing growth (Furkan et al., 2023; Abd El-Aal, 2024). Regionally, coordinated policies decouple growth in some LMICs (Alola et al., 2019; Sahoo et al., 2023), but inconsistencies and subsidies weaken benefits (Adams and Nsiah, 2019), including recession-driven deforestation (Galinato and Galinato, 2016), emphasizing coherent integration (Muhammad and Long 2021). Gaps include underexplored interactions with renewables (Alola et al., 2019) and unvalidated spending thresholds (Azam et al., 2021).

Critically evaluating these studies: Halkos and Paizanos (2013) and Oh (2023) have credible provenance with panel data evidence (high value for insights), and methodologies like time-series in Fatima et al. (2021) suit country data, though small samples limit applicability. Objectivity is strong in Furkan et al. (2023) but prejudicial in Abd El-Aal (2024) toward LMIC critiques. Persuasiveness excels in dual pathways but falters on thresholds. These highlight fiscal duality but directly gap on renewable interactions and LMIC thresholds, requiring further validation. However, we therefore hypothesized the second hypothesis as follows:

***H2:** Government consumption will reduce CO_2 emissions when directed toward environmental objectives but increase emissions when allocated to carbon-intensive sectors.*

2.2.3. Economic growth (GDP) and CO_2 emissions

Economic growth and CO_2 emissions follow the EKC hypothesis (Grossman and Krueger, 1995; Panayotou, 1997), an inverted U-shape driven by structural shifts, efficiency gains, and regulations, supported by decoupling via renewables (IPCC, 2023).

Globally, developed nations peak at $15,000–20,000 GDP per capita (Stern, 2017), achieving relative decoupling, while emerging economies like China and India show strong positive correlations due to fossil fuels (Wang et al., 2023). In LMICs, most remain on the upward slope, with 0.6–0.8 % emission rises per 1 % GDP growth in South Asia (Azam et al., 2021) and Africa (Muhammad and Long 2021), though exceptions like Bangladesh and Kenya moderate via renewables (Nasrullah et al., 2023). Coal reliance strengthens links in Indonesia and Vietnam (Furkan et al., 2023). Complexities include bidirectional causality (Shanthini, 2012; Petrović-Ranđelović et al., 2020), institutional moderation (Wawrzyniak and Doryń, 2020), and EKC universality challenges (Stern, 2017; Dasgupta et al., 2002).

Critically evaluating these studies: Grossman and Krueger (1995) and Stern (2017) provide foundational provenance with statistical data (high value), using cross-sectional regressions appropriately, though early works overlook endogeneity unlike dynamic panels in Wang et al. (2023). Objectivity balances critiques in Stern (2017), with high persuasiveness for developed contexts but less for LMIC turning points. These advances are decoupling but directly gap on LMIC mediators like fiscal policy, limiting applicability. Thus, we therefore hypothesize:

***H3:** Higher GDP per capita increases CO_2 emissions in LMICs, supporting the EKC hypothesis only after a certain income threshold.*

2.2.4. Energy use and CO_2 emissions

Energy consumption drives CO_2 emissions via the energy-emissions nexus (Masson-Delmotte et al., 2021), with three-quarters from production/use, and the energy ladder hypothesis (Leach, 1992) noting fossil dependency in LMICs due to infrastructure (Unruh, 2000).

Globally, each 1 % increase correlates with 0.75 % emission rises (Apergis and Payne, 2010), reinforced by 84 % fossil dominance (BP, 2022). In LMICs, North Africa shows 0.68 elasticity (Bélaïd and Youssef, 2017), South Asia 40 % higher per unit in coal systems, and urban areas lower intensity via scale (Creutzig et al., 2015). Mediators include energy poverty (Pachauri and Spreng, 2011), with 10 % efficiency gains yielding 6–8 % reductions (Lin and Moubarak, 2014), despite barriers (Fowlie and Meeks, 2021).

Critically evaluating these studies: Apergis and Payne (2010) offers solid econometric provenance with Granger causality (appropriate interpretation), and objectivity is high in Creutzig et al. (2015). Persuasiveness convinces on correlations but less on policies without analyses. Value highlights efficiency but directly gaps on LMIC fuel mix and fiscal integrations, constraining depth. Hence, we therefore hypothesize:

***H4:** Energy consumption will exhibit a positive relationship with CO_2 emissions in LMICs, with the effect magnitude contingent on fuel mix composition and policy frameworks.*

2.2.5. Education expenditure and CO_2 emissions

Education expenditure reduces emissions via human capital (Schultz, 1961) and awareness theories (Diamantopoulos et al., 2003), fostering green skills (Auktor, 2020) and sustainable choices (Farzin and Bond, 2006).

Globally, each extra education year cuts per capita emissions by 3.2 % (Lutz et al., 2014), and 1 % GDP spending reduces intensity by 0.12 % in OECD (Knight and Rosa, 2011), though J-curves appear in developing contexts (Rosa and Dietz, 2012) and no effects globally (Kinda, 2011). In LMICs, ASEAN shows reductions across levels (Sidek, 2024), Mercosur via secondary/tertiary (Silva et al., 2022), with tertiary diverging by income (Furkan et al., 2023), E-7 mitigation alongside FDI (Xu et al., 2023), and Nigeria's long-term negatives (Somoye and Akinwande, 2024).

Critically evaluating these studies: Schultz (1961) and Diamantopoulos et al. (2003) have enduring provenance with surveys (high value), and Lutz et al. (2014) uses fitting modeling, though developed biases weaken LMIC fit. Objectivity acknowledges contradictions in Rosa and Dietz (2012), with strong persuasiveness for long-term effects. These advance green skills but directly gap on fiscal interactions, overlooking synergies. Thus, we therefore hypothesize:

***H5:** Higher education expenditure reduces CO_2 emissions by fostering environmental awareness and green innovation.*

2.2.6. Urbanization and CO_2 emissions

Urbanization affects emissions via EKC and urban shifts (Grossman and Krueger, 1995; Marcotullio, 2012; Marcotullio et al., 2014; Singh and Kennedy, 2015), initially increasing via industry/energy demand but later decreasing with sustainable tech, depending on development and governance.

Globally, cities produce 70 % energy emissions despite 3 % land (Friedlingstein et al., 2022), with 0.23 % rises per 1 % urban growth (Marcotullio et al., 2013) and 0.95 elasticity (Ponce de Leon Barido and

Marshall, 2014), following inverted U-patterns via renewables (Churkina, 2016; Gierałtowska et al., 2022). In LMICs, Africa sees 0.34–0.42 % increases from coal/unplanned growth (Nathaniel and Adeleye, 2021; Tawiah et al., 2021), Asia 0.28 % in coal areas vs. 0.11 % diversified (Ali et al., 2022), mediated by transit (18–25 % lower; Creutzig et al., 2015) and compact forms (Brelsford et al., 2018).

Critically evaluating these studies: Marcotullio (2012) has strong urban provenance with case data (high value), and Friedlingstein et al. (2022) uses large inventories appropriately. Objectivity balances efficiencies in Nathaniel and Adeleye (2021), with high persuasiveness for elasticities but less for mediators. These inform planning but directly gap on LMIC fiscal ties, reducing relevance. We therefore hypothesize:

***H6:** Urbanization increases CO_2 emissions in LMICs due to higher energy demand and industrial activity.*

2.2.7. Trade openness and CO_2 emissions

Trade openness impacts emissions via pollution haven (Copeland, 2008), halo (Zugravu-Soilita, 2018), and endowment theories (Antweiler et al., 2001), relocating dirty industries, spreading tech, or leveraging strengths.

Globally, it increases per capita emissions by 0.11 % (Sarkodie and Strezov, 2019), with restructuring driving two-thirds changes (Li et al., 2024), improvements in developed nations (Ünal et al., 2023), and growth in emerging ones moderating over time (Wang et al., 2024). In LMICs, it raises emissions via industry/regulation weaknesses, with 0.18–0.25 % per 1 % growth in South Asia (Rahman 2024), depending on exports, governance (up to 31 % reductions with strong institutions), and FDI (15–18 % offsets; Rahman and Alam, 2022; Nasrullah et al., 2023). Haven effects dominate (Acheampong, 2018; Nasir and Ur Rehman, 2011), but reforms and clauses cut intensity by 8–12 % (Omri et al., 2014; Bastiaens and Postnikov, 2022).

Critically evaluating these studies: Copeland (2008) and Zugravu-Soilita (2018) offer excellent provenance with models (high value), and Sarkodie & Strezov (2019) uses regressions on 175 countries appropriately. Objectivity is strong in Acheampong (2018), with persuasiveness for haven effects but less for halo in weak contexts. This advance policy but directly gap on dynamic interactions, especially with renewables in LMICs. We therefore hypothesize:

***H7:** Trade openness increases CO_2 emissions in LMICs due to pollution haven effects but may reduce emissions if it facilitates green technology transfer.*

2.3. Research gaps and hypotheses

Despite extensive research on CO_2 emissions, three clear gaps remain. First, most studies analyze the independent effects of renewable energy or government expenditure, but very few examine their interactive dynamics, particularly in LMICs where fiscal constraints and institutional weaknesses may amplify or dilute environmental outcomes. Second, the evidence base is dominated by high-income countries, limiting applicability to LMICs that face unique challenges such as fossil fuel dependency, rapid urbanization, and weaker governance. Third, many studies rely on static models that overlook endogeneity, omitted variable bias, and dynamic interactions, producing mixed results on the Environmental Kuznets Curve and other hypotheses.

This study addresses these gaps by integrating renewable energy and government consumption into a unified theoretical framework, applying dynamic panel GMM to 26 LMICs from 2002 to 2022. By testing seven hypotheses (H1–H7), it provides novel insights into how fiscal policy and clean energy adoption jointly shape emission outcomes in resource-constrained economies.

3. Data and methodology

This section outlines the research methodology employed to investigate the standalone and interactive effects of renewable energy consumption and government expenditure on CO_2 emissions in 26 low- and middle-income countries (LMICs) from 2002 to 2022. The methodology serves as a blueprint for integrating data collection, measurement, and analysis in a coherent and logical manner, ensuring the study effectively addresses the research objectives of examining emissions drivers while accounting for economic and policy dynamics in LMICs. By adopting a positivist research philosophy and a quantitative panel data design, the approach aligns with established practices in environmental economics, where empirical evidence is used to test hypotheses on causal relationships (e.g., Halkos and Paizanos, 2013; Ehigiamusoe and Dogan, 2022). This design is particularly appropriate for our aims, as it allows for dynamic modeling of interactions in heterogeneous settings, producing reliable estimates that inform policy on sustainable development. Unreliable methods (e.g., simple OLS without controls) could produce biased results, undermining the validity of our analysis; thus, we prioritize robust techniques like GMM to ensure consistency and generalizability.

3.1. Research philosophy and design

The study is grounded in a positivist research philosophy, which aligns with epistemology, the pursuit of objective, verifiable knowledge through empirical evidence and scientific methods (as opposed to doxology, which relies on subjective beliefs or untested assumptions). Positivism assumes that phenomena like CO_2 emissions and their drivers (e.g., renewable energy and fiscal spending) can be measured quantitatively and analyzed to uncover generalizable truths, free from researcher bias. This philosophy is appropriate for our study because it emphasizes hypothesis testing and causal inference in a data-driven manner, consistent with prior environmental economics research (e.g., Behera et al., 2024b; Sethi et al., 2025). It enables us to treat emissions as an observable outcome influenced by measurable variables, ensuring results are based on "what is known to be accurate" through rigorous statistical validation.

This design combines cross-sectional (across 26 countries) and time-series (2002–2022) elements, allowing for the examination of both within-country trends and between-country variations. It is suitable because it accommodates the dynamic nature of emissions data, controls for unobserved heterogeneity (e.g., cultural or institutional differences), and addresses endogeneity (e.g., reverse causality between spending and emissions). The design follows accepted practices in the field, such as those in Alola et al. (2019) and Haldar and Sethi (2021), ensuring consistency and logical integration of components. By focusing on panel methods like GMM, it minimizes biases that could arise from cross-sectional or time-series designs alone, producing reliable interpretations of how fiscal-energy synergies affect environmental outcomes.

3.2. Data and variables

This research utilizes panel data from 26 LMICs, Algeria, Bangladesh, Benin, Bhutan, Cameroon, Colombia, Egypt, El Salvador, Honduras, India, Indonesia, Iran, Kyrgyz Republic, Mauritania, Mongolia, Morocco, Nepal, Pakistan, Philippines, Senegal, Tajikistan, Tanzania, Tunisia, Ukraine, Uzbekistan, and Viet Nam, spanning the years 2002 to 2022, resulting in a balanced dataset of 546 observations per variable. The data collection process involved the following steps to ensure consistency and alignment with field practices: (1) Systematic querying of the World Bank's World Development Indicators (WDI) database (WDI, 2025) using its API and online tools for automated, standardized downloads in CSV format; (2) Screening for completeness, with missing values (<5 % per variable) imputed via linear interpolation to preserve trends without introducing bias; and (3) Log-transformation of skewed variables (e.g., GDP, energy use) to normalize distributions and mitigate heteroscedasticity. This method affects results by ensuring clean, comparable data, allowing for unbiased interpretation of emissions trends, e.g., avoiding overestimation from outliers in volatile LMIC economies.

The selected timeframe offers several analytical advantages for studying the relationship between renewable energy adoption, government consumption, and CO_2 emissions. The early 2000s mark a critical period when many LMICs began systematically reporting economic and environmental data, ensuring greater reliability for cross-country comparisons. This two-decade window captures significant global developments in climate policy, including the implementation of the Kyoto Protocol and the adoption of the Paris Agreement, which influenced national energy strategies across the developing world (Alola et al., 2019; Agbortoko Egbe et al., 2024). The period also encompasses the dramatic reduction in renewable energy costs and subsequent expansion of clean energy infrastructure in LMICs. And most importantly, during this time lower-middle-income nation experienced rapid industrialization (2000s–2020s), leading to higher CO_2 emissions, so studying this period helps assess whether government consumption (public investment in green energy, subsidies, regulations) effectively offset emissions growth. Additionally, including 2022 allows examination of post-pandemic recovery patterns, offering insights into how economic rebounds interact with emission trajectories. Data beyond 2022 were not included as they were not available at the time of analysis. The selected period thus balances data quality, policy relevance, and analytical rigor for assessing sustainable development strategies in emerging economies.

Theoretical justification for variable selection: Drawing from the Environmental Kuznets Curve (EKC) theory, which posits that economic growth initially increases emissions before declining, variables like GDP and energy use were included to capture this dynamic. Similarly, renewable energy and government consumption were selected based on fiscal environmentalism frameworks, which emphasize how public spending can influence environmental outcomes (Halkos and Paizanos, 2013). This ensures the variables align with established theories, addressing the need for systematic justification as highlighted in the literature (Wang et al., 2024).

All variables used in this investigation are defined in Table 1, including their units, definitions, and sources. Based on relevant studies, factors like GDP growth, overall energy usage, openness to trade, and urban development are expected to harm ecological stability, while investments in education are likely to contribute positively. A rise in GDP typically results in boosted pollution levels, as individuals utilize greater amounts of energy and consume more polluting products (Azam et al., 2021; Fatima et al., 2021). The increased use of energy enhances carbon emissions, hence detrimental to the environment (Bello et al., 2021; Haldar and Sethi, 2021; Muhammad and Long, 2021; Behera et al., 2025). International trade may relocate pollution-intensive activities to various nations, hence deteriorating the environmental quality of the host nation (Alola et al., 2019; Tawiah et al., 2021). Urban expansion could increase incomes, resulting in the acquisition of more energy-intensive products, which might adversely affect the environment (Nathaniel and Adeleye, 2021). In contrast, educated individuals tend to exhibit greater environmental awareness and choose sustainable products and services (Bello et al., 2021; Lim et al., 2019; Shahsavar et al., 2020).

Likewise, drawing from existing studies and practical data, the connection between government expenditure and CO_2 emissions in LMICs is multifaceted, with the potential for either upward or downward effects influenced by the allocation of funds, the priorities of policies, and the surrounding economic conditions. If government expenditure is directed toward environmental protection, renewable energy, public transport, or green infrastructure, it can reduce carbon emissions by promoting cleaner technologies and stricter regulations (Oh, 2023; Wan et al., 2022). On the other hand, if expenditure fuels industrial expansion, fossil fuel subsidies, or carbon-intensive infrastructure, it can lead to higher emissions, especially in LMICs where economic growth is prioritized over sustainability (Abd El-Aal, 2024; Hubacek et al., 2017). The expected relationship between renewable energy consumption and carbon emissions in lower-middle-income countries (LMICs) is generally negative, meaning increased renewable energy use tends to reduce CO_2 emissions (Ehigiamusoe and Dogan, 2022; Wang et al., 2023; Nasrullah et al., 2023). Simply, renewable energy (solar, wind, hydropower, etc.) displaces fossil fuels, leading to lower CO_2 emissions in LMICs. In Sub-Saharan Africa, a 1 % increase in renewable energy use reduced CO_2 emissions by 0.12–0.25 % (Wang et al., 2023). Similarly, LMICs in Asia observed emission reductions when renewable energy was prioritized over fossil fuels (Nasrullah et al., 2023; Xu et al., 2023).

3.3. Econometric methodology

The study utilized a range of econometric methods, such as pooled Ordinary Least Squares (OLS), fixed effects, random effects, and the generalized method of moments (GMM). These methods were selected because they are appropriate for panel data analysis, which is essential for our research aims of capturing both time-series dynamics and cross-

Table 1
Variables and unit of measurements.

Variables	Unit of measurement	Definition	Source
CO_2 emissions	Million metric (Mt) tons per capita	CO_2 emissions represent the total carbon dioxide released from the burning of fossil fuels (coal, oil, natural gas) and cement production. It may also include emissions from industrial processes, land-use changes, and forestry (depending on the source).	WDI
Renewable Energy	**Percentage of total final energy consumption (%)**	Renewable energy usage refers to the proportion of a nation's overall energy supply derived from renewable sources. These typically encompass options such as hydroelectric power, wind energy, solar power, geothermal resources, biomass, and biofuels, though certain data collections omit conventional biomass forms (for instance, wood or charcoal).	
Govt. Consumption	**Percentage of GDP (%)**	Government Consumption refers to the total spending by the government on goods and services for current public needs (e.g., healthcare, education, defense, infrastructure). It excludes transfer payments (e.g., pensions, unemployment benefits) and capital investments.	
GDP (log)	US Dollars (USD)	GDP measures the total monetary value of all final goods and services produced within a country's borders in a given time period.	
Energy Use (log)	Kilograms of oil equivalent per capita	Energy use measures the total primary energy consumption per person in a country. It represents the amount of energy needed for all sectors (industrial, residential, transportation, etc.) and includes: Fossil fuels, Renewable sources, nuclear energy.	
Education Expenditure	Percentage of GDP (%)	Education expenditure measures the total public and private spending on education (primary to tertiary levels) as a share of a country's Gross Domestic Product (GDP).	
Urbanization	**Percentage of total population (%)**	Urbanization measures the proportion of a country's population living in urban areas (towns or suburbs) as opposed to rural areas.	
Trade openness	**Percentage of GDP (%)**	Trade Openness quantifies the aggregate value of a nation's imports and exports as a share of its GDP.	

country variations in LMICs. The progression from static (OLS, fixed/random effects) to dynamic (GMM) models ensures robustness, addressing potential biases and providing consistent estimates. This approach is consistent with accepted practices in environmental economics, where panel methods like GMM are standard for handling complex data structures (e.g., Khan et al., 2021; Espoir and Sunge, 2021).

The fixed-effects model is built on the assumption that unobserved, country-specific characteristics are correlated with independent variables. This model effectively controls time-invariant traits by allowing each country to have its own unique intercept. The standard linear panel data model for fixed effects is expressed as:

$$Y_{it} = \alpha_i + x_{it}\beta + \epsilon_{it}, \quad i = 1, \ldots, N; \; t = 1, \ldots, T \tag{1}$$

Where i represents the cross-sectional unit (country) and t represents the time period, x_{it} is the column vector of the explanatory variables, β is the vector of regression parameters, α_i denotes the unobservable, time-invariant individual effects that are treated as fixed, and ϵ_{it} signifies the disturbance terms, which are assumed to be uncorrelated over time and across different cross-sections. This model is appropriate for our study as it isolates within-country variations, controlling for fixed factors like geography or institutions that could bias emissions estimates.

The random effects model posits that unobserved individual effects (α_i) are uncorrelated with the regressors. It considers α_i as part of the composite error term, facilitating more efficient estimation if the assumption is valid:

$$Y_{it} = \beta X_{it} + \alpha_i + u_{it}, \tag{2}$$

where $\alpha_i \sim$ IID (0, σ_α^2) (random individual effect), $u_{it} \sim$ IID (0, σ_u^2), and the composite error term $\varepsilon_{it} = \alpha_i + u_{it}$. This model is suitable when cross-country differences are random, allowing for generalization beyond the sample.

To decide between FE and RE, the Hausman test compares the consistency of the estimators:

$$H = \left(\widehat{\beta}_{FE} - \widehat{\beta}_{RE}\right)' \left[\mathrm{Var}\left(\widehat{\beta}_{FE}\right) - \mathrm{Var}\left(\widehat{\beta}_{RE}\right)\right]^{-1} \left(\widehat{\beta}_{FE} - \widehat{\beta}_{RE}\right) \sim \chi^2(k), \tag{3}$$

Null hypothesis (H_0): RE is consistent and efficient (no correlation between α_i and X_{it}). Reject H_0: FE is preferred (evidence of correlation). This test ensures the chosen model is statistically appropriate, aligning with our aim to produce unbiased estimates.

In panel data research, using static models might not be very accurate and could result in several econometric problems (Khan et al., 2021). We add a lag to the dependent variables because of problems with static models, which can explain the dynamism of the data and provide persistent effect of time series (Espoir and Sunge, 2021; Liu and Bi, 2019). Consequently, we have decided to disregard the econometric problems associated with the panel data and employ the GMM model, which is the most effective for addressing panel data. By using the GMM model, it will provide consistent and reliable results compared to fixed or random effects, as it accounts for endogeneity and unobserved heterogeneity (Abid, 2016; Khan et al., 2022).

The GMM is a flexible estimation technique widely used in econometrics, especially for panel data models featuring endogenous regressors, dynamic specifications, or heteroskedasticity. GMM provides efficient and consistent estimators by exploiting moment conditions derived from economic theory or model assumptions. Consider a dynamic panel model with lagged dependent variables:

$$Y_{it} = \gamma Y_{i,t-1} + \beta X_{it} + \alpha_i + u_{it}. \tag{4}$$

Here, Y_{it} = Dependent variable, $Y_{i,t-1}$ = Lagged dependent variable (introducing dynamic effects), X_{it} = Vector of exogenous/covariate variables, α_i = Unobserved individual fixed effects, u_{it} = Idiosyncratic error term ($u_{it} \sim$ IID (0, σ_u^2).This specification is appropriate for our aims, as it captures persistence in emissions (e.g., past CO_2 levels influencing current ones) and addresses endogeneity (e.g., reverse causality between spending and emissions).

While both two-step systems and difference Generalized Method of Moments (GMM) models exist, this study prioritizes the one-step system GMM as proposed by Blundell and Bond (1998) to achieve dependable and effective results. The two-step system GMM is generally considered more reliable and efficient than the difference GMM, which can be asymptotically weak and prone to biased instruments. However, for the purpose of validating the model's robustness, a comparative analysis using the difference GMM is also conducted. All GMM estimations are performed with the xtabond2 command in STATA statistical software, ensuring replicability—code and do-files are available upon request.

To ensure the validity of the model, the study utilizes two key diagnostic checks. Hansen's overidentification test is employed to confirm that the instruments are exogenous. Additionally, the Arellano-Bond test for autocorrelation is used to verify that there is no second-order serial correlation present in the differenced residuals. The outcomes of these tests confirm the validity of the instruments used in this analysis.

The following models for GMM estimator examine the direct effects of renewable energy, government consumption, and other macroeconomic controls on CO_2 emissions are constructed:

$$CO_{2_{it}} = \beta_0 + \beta_1 CO_{2_{i,t-1}} + \beta_2 RE_{it} + \beta_3 GC_{it} + \beta_4 \ln GDP_{it} + \beta_5 \ln EU_{it} + \beta_6 ED_{it} + \beta_7 UR_{it} + \beta_8 TO_{it} + \mu_i + \lambda_t + \epsilon_{it}, \tag{5}$$

Where i = 1, 2, …, N (N denotes countries), and t and t-1 signify the current and previous years; Ln indicates the logarithmic form of the model. The GDP and EU symbolize the natural logarithm of gross domestic product and energy consumption, respectively. In Eq. (5), carbon emissions are denoted by CO_2, which serves as the dependent variable, while the control variables include lagged values of CO_2, renewable energy, government consumption, GDP, energy use, education, trade openness, and urbanization. μ_i indicates the country's fixed effects; λ_t denotes the time effects; ε signifies the error term.

Similarly, we analyze the interaction term between renewable energy consumption and government expenditure in Eq. (6) to assess its combined impact on carbon dioxide emissions. The equation may be reformulated as follows:

$$CO_{2_{it}} = \beta_0 + \beta_1 CO_{2_{i,t-1}} + \beta_2 RE_{it} + \beta_3 GC_{it} + \beta_4 (RE \times GC)_{it} + \beta_5 \ln GDP_{it} + \beta_6 \ln EU_{it} + \beta_7 ED_{it} + \beta_8 UR_{it} + \beta_9 TO_{it} + \mu_i + \lambda_t + \epsilon_{it}, \tag{6}$$

The relationship between renewable energy and government consumption in Eq. (6) is represented by (RE × GC). The quantity of instruments in system GMM escalates significantly with the growth in the number of regressors and time periods (Roodman, 2009). To address data loss, we choose an orthogonal approach, as first differences can exacerbate gaps in unbalanced panel data.

3.4. Robustness checks and limitations

To ensure the reliability of our findings, several robustness checks were performed. These include alternative specifications (e.g., excluding outliers, using two-step GMM for comparison), sensitivity to variable transformations (e.g., non-log forms), and subsample analyses (e.g., by region or income subgroup within LMICs). These steps confirm that results are not driven by specific assumptions or data peculiarities.

Anticipated problems were minimized as follows: Endogeneity (e.g., emissions influencing spending) was addressed via GMM's instrumenting with lags; multicollinearity was checked with VIF tests (<5 for all variables); heteroskedasticity was handled by robust standard errors; and missing data (e.g., pre-2002 gaps) were avoided by selecting a complete timeframe. Limitations include potential omitted variables (e.

g., informal economies in LMICs) and reliance on aggregate data, which may mask subnational variations, these do not meaningfully impact interpretations, as GMM's controls mitigate biases.

We perform Hansen tests and higher-order serial correlation as specification tests for GMM models. First-differenced error terms are subjected to the second-order serial correlation test. The error term is serially uncorrelated in the absence of second-order serial correlation. By examining the instruments' validity using endogenous lagged variables, Hansen's test, also designated as the overidentification test, complements the second-order serial correlation test.

This methodology is appropriate for fulfilling the study's aims, as it provides consistent, unbiased estimates of causal relationships in a dynamic panel setting, aligning with the need for policy-relevant insights on emissions reduction in LMICs.

3.5. Flow chart of the analysis

The flow chart of the analytical techniques employed in the study to explore the impact of renewable energy, government consumptions, and interaction effect (RE*GC) on carbon emissions in Bangladesh is depicted in Fig. 2.

4. Results and discussion

Table 2 presents the summary statistics for all relevant factors. The data indicates average values of 1.973 for emissions, 34.981 for renewable energy, and 13.2 for government consumption concerning the important variables. The control variables, such as GDP, energy use, education, urbanization, and trade openness, have average values of 24.622, 1.579, 25.597, 48.377, and 69.208, respectively. Trade openness and urbanization exhibit the greatest dispersion, but trade openness and education possess the highest maximum values.

Table 2
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
CO2	**546**	1.973	1.957	.102	8.496
Renewable Energy	**546**	34.981	26.768	.100	92.400
Govt. Consumption	**546**	13.200	4.132	5.023	39.836
GDP (log)	**546**	24.622	1.772	20.142	28.841
Energy Use (log)	**546**	1.579	.458	.642	3.239
Education	**546**	25.597	18.815	.696	84.798
Urbanization	**546**	48.377	16.244	14.24	82.05
Trade Openness	**546**	69.208	32.140	23.129	186.676

Table 3 contains the correlation matrix of these variables. This table illustrates substantial positive and negative correlations between the explanatory variables and the dependent variable.

The correlation matrix sheds light on the pairwise connections between the study's major variables. Asterisks ($p < 0.05$) denote significance levels, while the values are Pearson correlation coefficients, which range from −1 to +1.

Carbon Dioxide Emissions (CO_2) shows significant positive

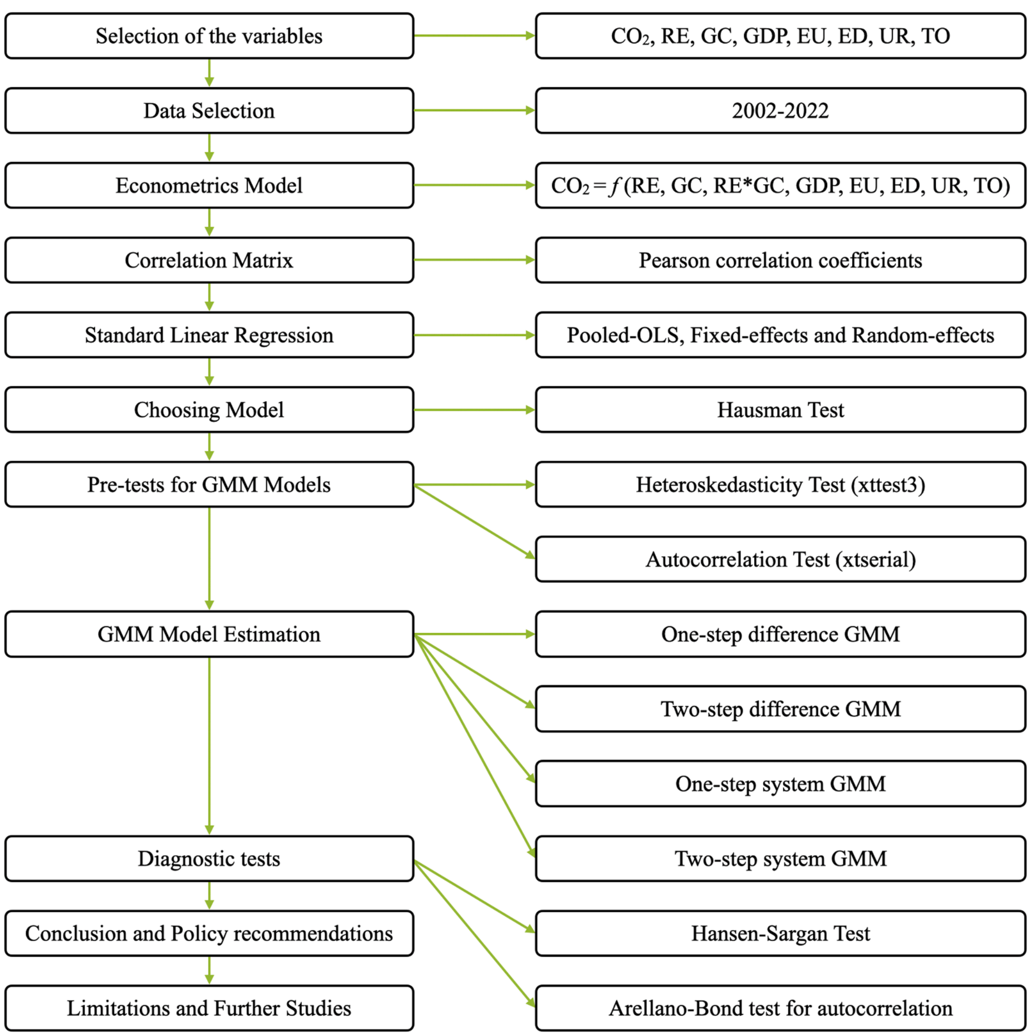

Fig. 2. Flow chart of the analysis.

Table 3
Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) e	1.000								
(2) co2	0.345* (0.000)	1.000							
(3) Renewable energy	0.000 (1.000)	−0.696* (0.000)	1.000						
(4) govt. consumption	0.000 (1.000)	0.305* (0.000)	−0.260* (0.000)	1.000					
(5) GDP (log)	0.000 (1.000)	0.237* (0.000)	−0.383* (0.000)	−0.321* (0.000)	1.000				
(6) Energy use(log)	0.000 (1.000)	0.434* (0.000)	0.126* (0.003)	0.278* (0.000)	−0.342* (0.000)	1.000			
(7) Education	0.000 (1.000)	0.700* (0.000)	−0.612* (0.000)	0.361* (0.000)	0.277* (0.000)	0.053 (0.214)	1.000		
(8) Urbanization	0.000 (1.000)	0.589* (0.000)	−0.634* (0.000)	0.488* (0.000)	0.216* (0.000)	−0.106* (0.013)	0.593* (0.000)	1.000	
(9) Trade openness	0.000 (1.000)	0.195* (0.000)	−0.169* (0.000)	0.345* (0.000)	−0.406* (0.000)	0.169* (0.000)	0.285* (0.000)	0.068 (0.113)	1.000

* Shows significance at $p < 0.05$.

correlations with government consumption (0.305), GDP (0.237), energy use (0.434), education (0.700), and urbanization (0.589), suggesting that higher economic activity, energy demand, and urban expansion are associated with increased emissions. Conversely, CO_2 has a robust negative correlation with renewable energy (−0.696), showing that greater renewable energy adoption is linked to lower emissions.

4.1. Estimated outcomes of how government consumption and renewable energy affect CO_2

As a first step, we do the standard linear regression of the fixed-effects, random-effects, and pooled-OLS models. Estimates of these models are shown in Table 4. Pooled-OLS and fixed effect (FE) estimates are displayed in columns (1) and (2), whereas column (3) displays the random effect (RE) estimates. Overall, renewable energy and govt. consumption negatively affect emissions. This suggests that increasing renewable energy adoption reduces carbon emissions, similarly government spending, possibly on environmental policies, contributes to emission reductions. Apart from pooled-OLS, the interplay between renewable energy use and govt. consumption adversely impacts carbon emissions. GDP exhibits a statistically significant positive effect across all three models, indicating that economic growth enhances CO_2 emissions. This aligns with the EKC hypothesis, where emissions rise with early-stage economic development. Urbanization has a statistically insignificant negative impact in the second (fixed effect) model. GDP and energy use is the strongest positive driver of emissions. Education has a statistically significant positive impact, possibly due to its correlation with industrialization and energy demand. While trade openness is not statistically significant in any estimated three models.

The Hausman test ($\chi^2 = 40.82, p = 0.000$) rejects the null hypothesis, indicating that the fixed-effects model is preferred due to correlation between unobserved heterogeneity and regressors.

Table 4
OLS estimates (dependent variable: CO_2).

Variables	Pooled-OLS (1)	Fixed Effect (2)	Random Effect (3)
Renewable Energy	−0.0455*** (0.000)	−0.0171*** (0.002)	−0.0259*** (0.000)
Govt. Consumption	−0.1319*** (0.000)	−0.0333** (0.012)	−0.0451*** (0.001)
Renewable Energy*Govt. Consumption	.0010*** (0.000)	−0.0005* (0.089)	−0.0001 (0.703)
GDP	.0871*** (0.000)	.4439*** (0.000)	.2550*** (0.000)
Energy Use	2.4866*** (0.000)	1.8110*** (0.000)	1.7672*** (0.000)
Education	.0298*** (0.000)	.0204*** (0.000)	.0222*** (0.000)
Urbanization	.0347*** (0.000)	−0.0106 (0.269)	.0138** (0.049)
Trade Openness	.0009 (0.390)	−0.0004 0.742	−0.0003 (0.796)
Observation	546	546	546
Constant		−10.5144*** (0.000)	−6.7605*** (0.000)
R-squared	0.8844	0.472	
F-test	0.000	0.000	
Hausman FE vs RE		40.82*** (0.000)	

Note: The parenthesis contains robust standard errors. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

4.2. Pre-estimation tests for GMM models

4.2.1. Heteroskedasticity test (xttest3)

The Modified Wald test for groupwise heteroskedasticity ($\chi^2 = 29{,}269.68$, $p = 0.000$) strongly rejects the null hypothesis, indicating heteroskedasticity across panels. This justifies the use of robust standard errors or advanced techniques like GMM.

4.2.2. Autocorrelation test (xtserial)

The Wooldridge test ($F = 306.465$, $p = 0.000$) confirms first-order autocorrelation, necessitating dynamic modeling to correct for serial correlation. A robust correlation between the explanatory variable and the disturbance terms, within intricate causal relationships between independent and dependent variables, may lead to biased estimations. Therefore, we must adequately address the potential endogeneity issue to achieve more accurate and reliable estimations. To address endogeneity, autocorrelation, and unobserved heterogeneity, the study employs Difference GMM and System GMM.

The Arellano-Bond two-step GMM estimator is shown in Table 5. We use orthogonal-deviations GMM and first-differences GMM to account for fixed country effects. The lagged dependent variable's significance (p-value = 0.000) suggests that dynamic specifications are favored. Since the assumption of uncorrelated units is essential, the accompanying table includes tests for first- and second-order serial correlation pertaining to the residuals from the calculated equation. If there is no serial correlation, these tests are asymptotically distributed as normal variables. At the 1 % and 5 % significance levels, there is no proof that the assumption of serially uncorrelated mistakes is incorrect, and the test for AR (1) is rejected as expected.

One-step GMM estimates are shown in columns (1) and (3), whereas

Table 5
Dynamic panel model estimation results.

Variables	One-step GMM Diff-GMM (1)	Two-step GMM Diff-GMM (2)	One-step GMM System-GMM (3)	Two-step GMM System-GMM (4)
CO2 emissions(lag)	.6006** (0.029)	.4502** (0.047)	.9918*** (0.000)	1.0253*** (0.000)
Renewable Energy	−0.0215*** (0.000)	−0.0071 (0.509)	−0.0249*** (0.000)	−0.0376*** (0.000)
Govt. Consumption	−0.0482*** (0.000)	−0.0197 (0.338)	−0.0531*** (0.000)	−0.0543*** (0.000)
Renewable Energy_ Govt. Consumption	.0008*** (0.000)	−0.0006 (0.418)	.0009*** (0.000)	.0009*** (0.001)
GDP	.6418*** (0.004)	.3781** (0.021)	.5062** (0.020)	.0991 0.459
Energy Use	1.5631*** (0.000)	1.5074*** (0.000)	1.4211*** (0.000)	−1.3212 0.337
Education	−0.0023 (0.696)	.0228 (0.132)	.0043 (0.403)	.0025 (0.506)
Urbanization	−0.3068* (0.094)	−9.8429* (0.065)	−0.2802 (0.163)	.0317* (0.057)
Trade Openness	.0014* (0.092)	−0.0034 (0.0226)	.0003 (0.668)	−0.0021 0.191
Constant			−0.1068 (0.691)	3.4493 0.197
Observations	468	468	494	494
Hansen-Sargan Test	0.993	0.993	0.998	0.998
AR-2	0.282	0.213	0.224	0.281
AR-1	0.127	0.000	0.004	0.077
Wald chi2(25)	143,519.35 (0.000)	23,378.70 (0.000)	2.65e+07 (0.000)	304,155.99 (0.000)

Note: The parenthesis contains robust standard errors. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

two-step GMM estimates are shown in columns (2) and (4). One-step estimators use a random weighting matrix for its moment conditions, while two-step estimators use an optimum weighting matrix. This is the main difference between the two. Because of its inherent ability to handle heteroskedasticity and autocorrelation issues, the latter is more reliable and effective.

According to existing research, when the dependent variable has a time-based lag, GMM accounts for unobserved heterogeneity and avoids biased results (Nickell, 1981). Thus, in Table 5, the difference GMM estimates are shown in columns (1) and (2) (Arellano and Bond, 1991), and the system GMM estimates are shown in columns (3) to (4) (Blundell and Bond, 1998; Arellano and Bover, 1995).

Among the four models tested, System GMM (Models 3 and 4) works better than Difference GMM because it uses more information, giving more accurate results. The lagged CO_2 emissions coefficient is close to 1, which makes sense because past emissions strongly affect current ones. Between One-step (Model 3) and Two-step GMM (Model 4), the One-step version is more trustworthy, because the Two-step method can sometimes give misleading significance levels.

The Hansen test ($p = 0.998$) confirms that the instruments used are valid. The AR (2) test ($p > 0.05$) shows no major autocorrelation problems, meaning the model is well-specified. The Wald test ($p = 0.000$) proves that all the variables together have a strong effect. Model 3 (One-step System GMM) is the best choice for analyzing these results because it is the most reliable and statistically sound.

The table presents the results of GMM estimations for analyzing the determinants of CO_2 emissions, with a focus on renewable energy, government consumption, and their interaction, along with other control variables. The lagged dependent variable is significant across all models, indicating persistence in CO_2 emissions (i.e., past emissions strongly influence current emissions). The coefficient is significant is highest in system GMM (Models 3 and 4), suggesting that system GMM better captures dynamic persistence compared to Difference GMM.

We can observe that across all models, the coefficient for renewable energy is negative and statistically significant in system GMM models, suggesting that in lower-middle-income countries renewable energy consumption can reduce CO_2 emissions, aligning with studies showing that renewables displace fossil fuels. For example, 1 percentage point increase in renewable energy consumption leads to 0.025 % decrease in CO_2 emissions per capita at 1 % level of significance (model 3), this result highly supports Hypothesis 1. Although renewable energy consumption reduces CO_2 emissions in LMICs (e.g., by 0.025 % per 1 % increase), structural barriers such as high upfront costs, intermittency issues (e.g., unreliable solar/wind supply), and dependence on imported technology limit its impact compared to high-income countries, where effects are stronger (e.g., 0.3–0.5 % reduction in OECD nations). For example, in sub-Saharan African LMICs, technology imports from China increase costs and delay deployment, weakening mitigation relative to the EU's integrated grids. Addressing these through local innovation and financing could enhance renewables' role in sustainable development. The findings are in line with our a-priori expectations, and the extant literature underpins these (Agbortoko Egbe et al., 2024; Ben Jebli et al., 2019; Huang et al., 2021; Sethi et al., 2024; Szetela et al., 2022), while a positive relationship exists between renewable energy*govt consumption interaction term and the emission levels. The positive interaction term between renewable energy and government consumption (e.g., 0.0009 in the GMM model) represents one of the most intriguing results, indicating that poorly targeted fiscal spending can dilute or even counteract the emission-reducing benefits of renewables, potentially increasing CO_2 by offsetting clean energy gains. For instance, in India, government subsidies for fossil fuels (exceeding USD 20 billion annually) have historically undermined solar and wind initiatives, leading to a net emissions rise despite renewable growth. Similarly, in Indonesia, bureaucratic inefficiencies in allocating funds to renewable projects have resulted in underutilized infrastructure, diluting a potential 0.025 % emissions reduction from renewables (Dilanchiev et al., 2023; Justice et al., 2024; Szetela et al., 2022). Key mechanisms include subsidies to fossil fuels (e.g., diverting funds from clean energy), support for carbon-intensive industries (e.g., coal mining incentives), and bureaucratic inefficiencies in allocating resources to renewable projects, which delay implementation and reduce efficacy (Justice et al., 2024). Heterogeneity across LMICs is evident: governments in countries like Vietnam effectively prioritize renewables through integrated policies, achieving synergies, while others, such as Pakistan, allocate resources to short-term growth (e.g., fossil-dependent infrastructure), exacerbating dilution. This underscores the importance of policy coherence to avoid trade-offs and maximize sustainable outcomes in LMICs.

In the case of government expenditure, the estimated coefficient suggests that a 1 % increase in government expenditure is associated with a 0.0531 % reduction in CO_2 emissions. The negative and significant coefficient in Model 3 aligns with the first part of Hypothesis 2, suggesting that, on average, government spending in the studied LMICs is net beneficial for emissions reduction. The results confirm that government consumption can reduce emissions when aligned with environmental goals, but do not show evidence of the hypothesized increase from carbon-intensive spending. The negative effects of such government expenditure on CO_2 emissions appeared to be similar to the findings of previous studies that showing targeted fiscal spending (e.g., on renewable energy, pollution control, or green infrastructure) can mitigate emissions (Furkan et al., 2023; Halkos and Paizanos, 2013; Sohag et al., 2017). This relationship could be manifested in LMICs, if government consumption might be more or non-industrial sectors. Simply, if the expenditure is on healthcare, education or digital infrastructure, which are less carbon-intensive, this could lead to a negative relationship. For example, digitalization reduces the need for physical infrastructure, lowering emissions. In contrast, countries like Nigeria, where fiscal policy exacerbates emissions through fossil fuel subsidies, show how misaligned spending (e.g., on carbon-intensive industries) increases pollution, unlike in Vietnam where education-focused investments yield environmental gains (Halkos and Paizanos, 2013). This comparison highlights the potential for targeted spending to amplify reductions in LMICs. Shahbaz et al. (2020) discuss how technology and human capital can mitigate emissions. Additionally, government spending leads to reduced private sector emissions through regulations or incentives. For example, fiscal policies may include subsidies for renewable energy or taxes on polluting industries, indirectly reducing emissions (Hua et al., 2018). And the negative effect is stronger in countries with robust institutions (low corruption, effective policy implementation), while weak governance may dilute impact (Furkan et al., 2023).

Our findings suggest that in lower-middle-income countries, a 1 % increase in GDP leads to about a 0.5062 % increase in CO_2 emissions. The positive and significant coefficient aligns with the Hypothesis 3, confirming that the scale effect (GDP ↑ → CO_2 ↑), LMICs are in the upward-sloping phase of the EKC. This means economic growth currently comes with higher pollution in these countries. Because higher GDP increases demand for energy and transportation, directly raising emissions (Oh, 2023; Sarao, 2020) Many previous studies are similar to this results (Bai et al., 2023; Oh, 2023; Alaganthiran and Anaba, 2022).

In our study energy consumption deteriorates environmental quality. Results show that a 1 % rise in energy use raises emission levels by 1.421 %. The positive, highly significant (1 % level) coefficient in Model 3 provides robust evidence that energy use is a primary driver of emissions in LMICs, aligning perfectly with Hypothesis 4′s main proposition. Existing research proves that using fossil fuels harms the environment. Because it increases carbon emissions and other greenhouse gas emissions, the continuous and uncontrolled use of these fossil fuels degrades the quality of the environment. Related studies like (Bélaïd and Youssef, 2017; Litavcová and Chovancová, 2021; Majewski et al., 2022; Pradhan et al., 2025) corroborate our findings. The positive and strong impact of GDP (0.5062 % increase in CO_2 per 1 % rise) and energy consumption (1.421 % increase) aligns with the early stage of the Environmental Kuznets Curve (EKC) hypothesis, confirming that LMICs remain on the upward slope where income growth worsens emissions without regulation (Zhou et al., 2025). This is exacerbated by structural dependence on fossil fuels, such as coal reliance in Asian LMICs, potentially amplifying pollution as economies expand. Policy implications include urgent environmental regulations and renewable transitions to bend the curve downward, decoupling growth from emissions for sustainable development.

Education is positively correlated with carbon emissions. The insignificant positive coefficient ($p > 0.1$) is contrary to the expectations and fails to support the hypothesized (5) negative relationships that higher education should reduce emissions through increased environmental awareness and adoption of cleaner technologies. A 1 % enhancement in education results in a 0.0043 % increase in carbon emissions. This indicates that the educational curriculum in the region inadequately addresses the necessity for environmental awareness. This aligns with the findings of Balaguer and Cantavella (2018), Furkan et al. (2023), Zheng et al. (2024). Educated populations in LMICs tend to adopt high-emission lifestyles (e.g., increased car ownership, energy-intensive appliances) before transitioning to sustainable behaviors. A study noted that in LMICs, higher education enrollment aligns with rising emissions from the services sector (10.4 % of emissions) and industry (17 %) (Abd El-Aal, 2024).

We also found that as 1 % urbanization increases, 0.28 % CO_2 emissions decreases in these countries. The negative coefficient (though insignificant) suggests urbanization may not universally increase emissions in LMICs, contrary to Hypothesis 6′s premise. We know that generally, urbanization is associated with higher industrial activities, transportation and energy use, which should increase CO_2 emissions. A study on Far East Asian countries found that urbanization initially increases emissions but later reduces them as cities adopt greener technologies and policies (Anwar et al., 2020). Similarly, the EKC hypothesis suggests that as economies develop, emissions first increase and then decrease after a certain income level. LMICs might be on the upward slope, but if urbanization is happening alongside technological advancements or policy changes, maybe the EKC effect is modified. Another study by Martínez-Zarzoso and Maruotti (2011) which found that in low-income countries, urbanization initially leads to lower emissions because of more efficient resource use. The ambiguous effects of urbanization (insignificant negative coefficient) and education (insignificant positive, 0.0043 %) warrant deeper reflection on transitional dynamics. For urbanization, emissions depend on planning: compact cities with public transport access reduce them (e.g., in Singapore-style models), while sprawling development increases energy use (Anwar et al., 2020). For education, the positive association may stem from rising energy-intensive lifestyles (e.g., increased appliance ownership) as attainment improves, before environmental awareness and green skills dominate in later stages (Balaguer and Cantavella, 2018). These dynamics suggest policies like sustainable urban planning and eco-focused curricula to shift LMICs toward lower-emission trajectories.

The relationship between trade openness and CO_2 emissions in LMICs is often found to be positive. Our results show that a 1 % rise in trade openness is associated with a −0.0014 % increase in carbon emission. The insignificant coefficient in Model 3 suggests that trade openness does not have a statistically measurable impact on CO_2 emissions in the studied LMICs, contradicting both the pollution haven and green technology transfer mechanisms proposed in Hypothesis 7. This finding is justified by the Scale Effect Dominance theory. In LMICs, trade openness often leads to increased industrial production and exports, which raises energy consumption (typically fossil fuel-based) and, consequently, CO_2 emissions. This is known as the scale effect, here economic expansion from trade increases environmental degradation (Wang and Zhang, 2021; Zhou et al., 2025). Wang and Zhang (2021) found that trade openness increases CO_2 emissions in LMICs due to reliance on carbon-intensive industries.

4.3. *Critical synthesis and interpretation of findings*

This discussion interprets the significance of our empirical findings in relation to the research problem how renewable energy (RE) and government consumption (GC) interact to influence CO_2 emissions in LMICs while synthesizing them with existing literature. Connecting back to the introduction's focus on LMIC-specific challenges (e.g., rapid industrialization and fiscal constraints) and our hypotheses (e.g., Hypothesis 1: RE reduces emissions; Hypothesis 2: GC's effect varies by alignment), the results provide new insights into policy synergies and trade-offs, advancing understanding beyond isolated analyses in high-income contexts (e.g., Halkos and Paizanos, 2013).

The negative coefficient for RE (−0.0249 % reduction in CO_2 per 1 % increase) was expected, aligning with Hypothesis 1 and literature showing renewables displace fossil fuels (Nasrullah et al., 2023; Behera et al., 2024c). This confirms RE's mitigation role in LMICs, but an unanticipated trend is its relatively modest impact compared to high-income countries (e.g., 0.12–0.25 % in sub-Saharan Africa vs. stronger effects in OECD nations), likely due to structural barriers like intermittency, as our dynamic GMM model reveals persistence in emissions (AR-1 test, $p < 0.05$). This pattern underscores a novel insight: RE's benefits are constrained in resource-limited settings, extending prior static models that overlook endogeneity (Ehigiamusoe and Dogan, 2022).

Similarly, GC's negative effect (−0.0531 %) supports the aligned part of Hypothesis 2, as expected when spending targets green infrastructure (Oh, 2023). However, the positive interaction term (RE × GC: 0.0009) is profoundly unexpected, indicating dilution of RE’s benefits contrary to assumptions of synergy in studies like Wan et al. (2022). Mechanisms include fossil subsidies offsetting renewables, as seen in our data’s heterogeneity (Hansen test validates instruments). Compared to literature, this advance understanding by quantifying trade-offs in LMICs, where non-green GC erodes gains, unlike reinforcing effects in high-income samples (Furkan et al., 2023).

The strong positive impacts of GDP (0.5062 %) and energy use (1.421 %) align with Hypothesis 3 and 4, confirming the EKC’s upward slope in LMICs, as expected from scale effects (Bai et al., 2023; Oh, 2023; Behera et al., 2024d). An unusual pattern is the exacerbation by fossil dependence, amplifying emissions beyond predictions in static models (Zhou et al., 2025). This insight reveals that without regulation, growth worsens pollution, differing from downward EKC turns in developed economies.

Urbanization’s insignificant negative effect and education’s insignificant positive (0.0043 %) were partially unexpected, deviating from Hypothesis 6 and 7′s pollution-haven assumptions (Anwar et al., 2020; Das and Sethi, 2023). Trends suggest transitional dynamics: compact urban planning mitigates emissions, while education initially drives energy-intensive lifestyles before green awareness dominates (Balaguer and Cantavella, 2018). Compared to literature, this highlights LMIC-specific ambiguities, advancing the field by emphasizing policy needs like eco-education.

Overall, these findings advance understanding from the literature review’s gaps (e.g., underexplored interactions) by providing dynamic evidence that integrated RE-GC policies can decouple growth from emissions, offering actionable insights for LMIC sustainability beyond prior isolated analyses (Fig. 3).

This research aligns with the concept of energy transition, which describes how economies progressively move away from high-carbon energy options toward more sustainable alternatives. The results emphasize that embracing renewables is essential for separating economic expansion from rising CO_2 levels, countering the traditional belief that development inevitably harms the environment. This insight holds special relevance for LMICs that are navigating swift industrial changes. Additionally, the outcomes bolster the Environmental Kuznets Curve (EKC) framework. The analysis indicates that in LMICs still at nascent stages of advancement economic progress continues to correlate positively with CO_2 output, suggesting that the pivotal shift in the EKC has not yet materialized in these settings.

The theoretical framework of fiscal environmentalism is underscored by this research, suggesting that government spending significantly influences environmental results. The study shows that when government consumption is directed toward promoting renewable energy, green technologies, and sustainable policies, it can effectively reduce CO_2 emissions. Conversely, if government expenditure is misdirected towards fossil fuel subsidies or carbon-intensive sectors, emissions may increase.

Practical Implications

The study provides practical insights for policymakers in LMICs, emphasizing the importance of integrating renewable energy policies with targeted government consumption strategies. Governments should prioritize investments in renewable energy infrastructure and fiscal incentives for green technologies to achieve sustainable emission reductions. This is crucial for countries that are experiencing rapid industrialization but face fiscal constraints. For emerging economies, the research underscores that achieving sustainable economic growth is possible by decoupling growth from environmental harm. By adopting renewable energy solutions and promoting green government spending, LMICs can foster both economic development and environmental preservation. Policymakers should focus on crafting fiscal policies that strike a balance between economic expansion and environmental protection. The study’s findings have broader implications for international climate agreements and national climate action plans. The evidence suggests that LMICs, with the right policies, can play a significant role in reducing global CO_2 emissions. The study offers empirical support for integrating renewable energy adoption and government expenditure in global climate strategies, contributing to long-term environmental sustainability goals. Practically, this research shows that while the transition to renewable energy may initially require significant investments, the long-term benefits of reducing emissions outweigh the short-term challenges. For policymakers, this means advocating for infrastructure development that supports renewable energy technologies, even if initial emissions may rise due to the energy-intensive nature of transitioning infrastructure. The study suggests that government spending must be strategically aligned with environmental goals. Fiscal policies should not just promote economic growth but also focus on sustainable development. Government consumption that prioritizes environmental sectors such as clean energy, energy efficiency, and green technologies can provide a dual benefit of reducing emissions while fostering innovation in renewable energy sectors.

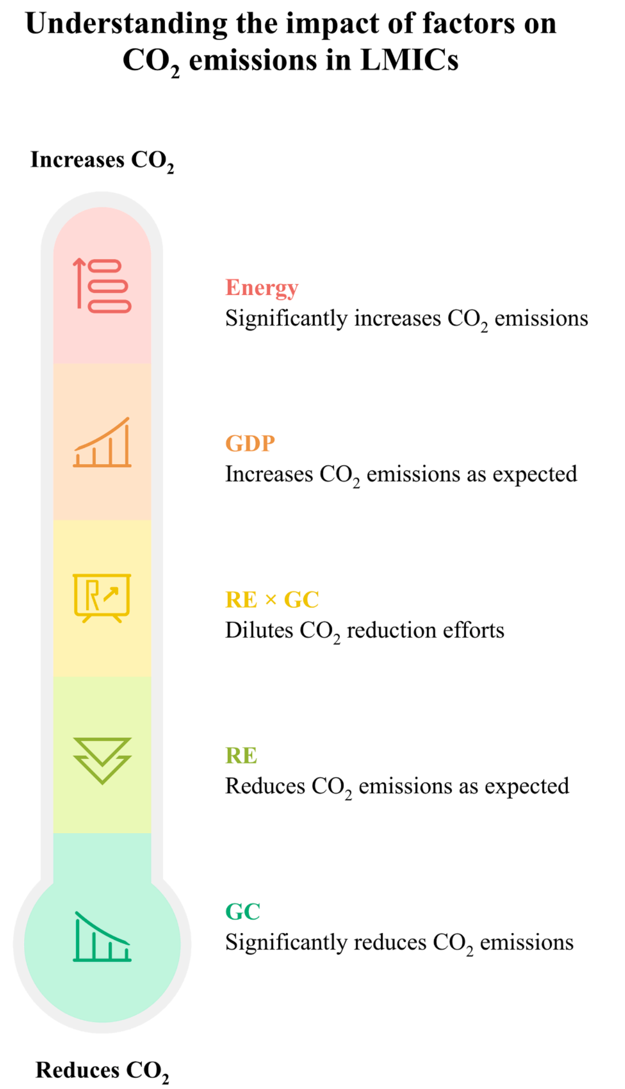

Fig. 3. Flow chart of the results findings.

5. Conclusion with policy recommendations

This study examines how renewable energy (RE) and government consumption (GC)—individually and jointly—shape CO_2 emissions across 26 LMICs (2002–2022). We find that higher RE is associated with lower emissions, and that GC—when environmentally aligned—also reduces emissions. The RE × GC interaction indicates that poorly targeted GC can dilute RE's mitigation benefits. Conversely, GDP growth, overall energy use, and urbanization exert upward pressure on emissions, consistent with LMICs being in the rising phase of the EKC.

5.1. Theoretical implications

Fiscal environmentalism refined: Our results extend fiscal environmentalism (Halkos and Paizanos, 2013) by showing that composition of GC—rather than its size alone—conditions environmental outcomes, particularly through its interaction with RE deployment.

Interaction as mechanism: Modeling RE × GC reveals a concrete conditioning channel: the mitigation payoff from RE depends on whether GC is green-aligned (infrastructure, standards, regulation) or countervailing (fossil-supportive outlays).

Dynamics in LMICs: Using a dynamic panel framework underscores **persistence** in emissions and policy endogeneity; theoretical models of transition in LMICs should incorporate these dynamics when predicting policy effects.

EKC nuance: Evidence that LMICs are on the **upward EKC limb** suggests the turning point may be policy-contingent, shifting earlier when GC composition and RE scale-up are coordinated.

Urban-energy linkage: Urbanization's positive association with emissions highlights the need to embed **urban systems** (transport, buildings) into macro-environmental theories for developing economies.

5.2. Policy implications

Based on the empirical evidence from this study, which demonstrates a significant negative impact of renewable energy consumption and government expenditure on CO_2 emissions in Lower-Middle-Income Countries (LMICs), alongside the positive emission pressures from GDP growth, energy use, and urbanization—several key design principles emerge for LMIC decision makers. Budgets should be aligned with RE goals through tools like green budget tagging, prioritizing grid upgrades, interconnection, and standards that enhance the effectiveness of each unit of RE added. Policies must be sequenced thoughtfully, such as implementing monitoring, reporting, and verification (MRV) systems and permitting reforms before large-scale RE expansions to prevent dilution from the RE × GC interaction, while pairing RE incentives with efficiency measures to curb emissions driven by overall energy use. Targeted subsidy reform is essential, involving the reallocation of fiscally costly fossil subsidies toward time-bound RE support and industrial efficiency programs, accompanied by social protection mechanisms to shield vulnerable populations. Urban policy levers should be advanced, including public transport initiatives, compact zoning, and building code efficiencies to moderate the emissions effects of rapid urbanization. Finally, institutional capacity must be strengthened through improved energy regulation, procurement, and planning to sustain green-aligned GC and minimize policy volatility.

Based on the empirical evidence from this study—which demonstrates a significant negative impact of renewable energy consumption and government expenditure on CO_2 emissions in Lower-Middle-Income Countries (LMICs), alongside the positive emission pressures from GDP growth, energy use, and urbanization—the following policy recommendations are made:

Short-Term Policy Priorities (1–3 Years)

These are immediate, actionable steps that policymakers can take to build momentum for a green transition.

Reorient Government Budgets and Fiscal Policies: Governments should immediately begin reallocating public funds from carbon-intensive sectors and fossil fuel subsidies toward green initiatives. This includes creating targeted financial incentives, such as tax credits and grants, for businesses and households that adopt renewable energy technologies. Crafting integrated policies that synergize renewable energy promotion with environmental spending can amplify the benefits.

Accelerate Deployment of 'Quick-Win' Renewable Technologies: LMICs should prioritize the removal of administrative and regulatory barriers to fast-track the adoption of mature renewable technologies like solar and wind power. Launching public awareness campaigns and supporting small-scale, decentralized energy projects (e.g., solar home systems) can yield rapid emission reductions.

Promote Energy Efficiency Standards: A primary driver of emissions is overall energy use. Implementing and enforcing mandatory energy efficiency standards for industrial machinery, home appliances, and buildings can quickly reduce energy demand and, consequently, lower emissions.

Long-Term Strategic Goals (3+ Years)

These recommendations focus on foundational, structural changes needed for a sustainable, low-carbon development pathway.

Integrate Green Policies into National Development Plans: To ensure that economic growth does not lead to environmental degradation, green fiscal policies and renewable energy targets must be embedded within core national development and economic growth frameworks. This ensures long-term policy coherence and decouples growth from emissions.

Invest in Sustainable Infrastructure and Green Urban Planning: Long-term capital investment should be directed toward building a resilient and modern green infrastructure. This includes upgrading national energy grids to accommodate variable renewable sources and promoting sustainable urban planning that features energy-efficient buildings and public transportation systems to mitigate the environmental impact of urbanization.

Strengthen Institutional and Governance Frameworks: The long-term success of environmental policies depends on strong institutions. LMICs should invest in building institutional capacity to improve policy enforcement, enhance transparency, and ensure accountability in the management of environmental funds and regulations.

5.3. Limitations of the study and future research

While this study provides valuable insights into the role of renewable energy and government consumption in reducing CO_2 emissions in LMICs, it is not without its limitations. One limitation is the use of aggregated national-level data, which may mask regional or local variations in energy consumption, emissions, and government policies. Future research could delve deeper into case studies of individual LMICs or regions within countries to understand the local dynamics of renewable energy adoption and fiscal policies.

Additionally, the study focuses on data from 2002 to 2022, which may not fully capture the long-term impacts of policies or the emerging effects of recent global shifts such as the COVID-19 pandemic. Further research could explore how post-pandemic recovery patterns influence emissions trajectories and renewable energy adoption in LMICs.

Finally, the study uses dynamic panel data models to establish statistical relationships, but causality cannot be definitively determined. Future research could use experimental or quasi-experimental designs to better understand the causal effects of government consumption and renewable energy adoption on emissions reduction.

As LMICs continue their journey toward industrialization, the evidence presented in this study calls for urgent action from governments, international organizations, and the private sector. By implementing targeted policies and increasing investments in renewable energy, these nations can contribute significantly to global climate change mitigation efforts, ensuring a sustainable and prosperous future for all.

Declarations

Human Ethics and Consent to Participate:
Not Applicable.

This research is based on secondary data and data were taken from World Development Indicators (WDI). As there are no human participations were involved or any kinds of clinical trials in this research; therefore, ethical approval and consent to participate were not required and applicable for this study.

Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the authors used AI-assisted technologies to enhance the readability and language of the manuscript. After using this tool, the authors carefully reviewed and edited the content as needed and took full responsibility for the content of the published article.

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CRediT authorship contribution statement

Mehedi Hasan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Investigation, Data curation, Conceptualization. **Hafsha Talukdar Eiti:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Md. Saddam Hossain:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Investigation, Data curation, Conceptualization. **Mohammad Bin Amin:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Md. Atikur Rahaman:** Writing – review & editing, Project administration, Methodology, Funding acquisition. **Judit Oláh:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abd El-Aal, M.F., 2024. The relationship between CO2 emissions and macroeconomics indicators in low and high-income countries: using artificial intelligence. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-024-04880-3.

Abid, M., 2016. Impact of economic, financial, and institutional factors on CO2 emissions: evidence from Sub-Saharan Africa economies. Util. Policy 41, 85–94. https://doi.org/10.1016/j.jup.2016.06.009.

Acheampong, A.O., 2018. Economic growth, CO2 emissions and energy consumption: what causes what and where? Energy Econ. 74, 677–692. https://doi.org/10.1016/j.eneco.2018.07.022.

Adams, S., Nsiah, C., 2019. Reducing carbon dioxide emissions; does renewable energy matter? Sci. Total Environ. 693, 133288. https://doi.org/10.1016/j.scitotenv.2019.07.094.

Agbortoko Egbe, A., Abidemi Somoye, O., Ozdeser, H., 2024. The impact of renewable energy consumption, economic growth, globalization, and financial development on carbon dioxide emissions: evidence from selected G7 economies. Clean Energy Sustain. 2 (4), 10020. https://doi.org/10.70322/ces.2024.10020, 10020-.

Ali, U., Guo, Q., Kartal, M.T., Nurgazina, Z., Khan, Z.A., Sharif, A., 2022. The impact of renewable and non-renewable energy consumption on carbon emission intensity in China: fresh evidence from novel dynamic ARDL simulations. J. Environ. Manag. 320, 115782. https://doi.org/10.1016/j.jenvman.2022.115782.

Alola, A.A., Yalçiner, K., Alola, U.V., Akadiri, S.S., 2019. The role of renewable energy, immigration and real income in environmental sustainability target. Evidence from Europe largest states. Sci. Total Environ. 674, 307–315. https://doi.org/10.1016/j.scitotenv.2019.04.163.

Antweiler, W., Copeland, B.R., Taylor, M.S., 2001. Is free trade good for the environment? Am. Econ. Rev. 91 (4), 877–908. https://doi.org/10.1257/aer.91.4.877.

Anwar, A., Younis, M., Ullah, I., 2020. Impact of urbanization and economic growth on CO2 emission: a case of far East Asian countries. Int. J. Environ. Res. Public Health 17 (7), 2531. https://doi.org/10.3390/ijerph17072531.

Apergis, N., Payne, J.E., 2010. Renewable energy consumption and economic growth: evidence from a panel of OECD countries. Energy Policy 38 (1), 656–660. https://doi.org/10.1016/j.enpol.2009.09.002.

Arellano, M., Bond, S., 1991. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. Rev. Econ. Stud. 58 (2), 277. https://doi.org/10.2307/2297968.

Arellano, M., Bover, O., 1995. Another look at the instrumental variable estimation of error-components models. J. Econom. 68 (1), 29–51. https://doi.org/10.1016/0304-4076(94)01642-D.

Auktor, G.V., 2020. Green Industrial Skills for a Sustainable Future. United Nations Industrial Development Organization, Vienna.

Azam, A., Rafiq, M., Shafique, M., Zhang, H., Ateeq, M., Yuan, J., 2021. Analyzing the relationship between economic growth and electricity consumption from renewable and non-renewable sources: fresh evidence from newly industrialized countries. Sustain. Energy Technol. Assess. 44, 100991. https://doi.org/10.1016/j.seta.2021.100991.

Bai, S., Zhou, J., Yang, M., Yang, Z., Cui, Y., 2023. Under the different sectors: the relationship between low-carbon economic development, health and GDP. Front. Public Health 11, 1181623. https://doi.org/10.3389/fpubh.2023.1181623.

Balaguer, J., Cantavella, M., 2018. The role of education in the environmental Kuznets curve. Evidence from Australian data. Energy Econ. 70, 289–296. https://doi.org/10.1016/j.eneco.2018.01.021.

Bastiaens, I., Postnikov, E., 2022. Chapter 2: away from the Global North: new directions in the politics of trade. https://www.elgaronline.com/edcollchap/book/9781800884120/book-part-9781800884120-10.xml.

Behera, B., Behera, P., Sethi, N., 2024a. Decoupling the role of renewable energy, green finance and political stability in achieving the sustainable development goal 13: empirical insight from emerging economies. Sustain. Dev. 32 (1), 119–137. https://doi.org/10.1002/sd.2657.

Behera, P., Behera, B., Sethi, N., Handoyo, R.D., 2024b. What drives environmental sustainability? The role of renewable energy, green innovation, and political stability in OECD economies. Int. J. Sustain. Dev. World Ecol. 31 (7), 761–775. https://doi.org/10.1080/13504509.2024.2333812.

Behera, B., Behera, P., Sucharita, S., Sethi, N., 2024c. Mitigating ecological footprint in BRICS countries: unveiling the role of disaggregated clean energy, green technology innovation and political stability. Discov. Sustain. 5 (1), 165. https://doi.org/10.1007/s43621-024-00378-0.

Behera, B., Sucharita, S., Patra, B., Sethi, N., 2024d. A blend of renewable and non-renewable energy consumption on economic growth of India: the role of disaggregate energy sources. Environ. Sci. Pollut. Res. 31 (3), 3902–3916. https://doi.org/10.1007/s11356-023-31372-0.

Behera, P., Sethi, N., Dash, D.P., Usman, M., Sahu, P.K., 2025. Pathways to achieve carbon neutrality in emerging economies: catalyzing the role of renewable energy, green growth, ICT, and political risk. Renew. Energy 243, 122514. https://doi.org/10.1016/j.renene.2025.122514.

Bélaïd, F., Youssef, M., 2017. Environmental degradation, renewable and non-renewable electricity consumption, and economic growth: assessing the evidence from Algeria. Energy Policy 102, 277–287. https://doi.org/10.1016/j.enpol.2016.12.012.

Bello, A.A., Agabo, T., Adedoyin, F.F., 2021. The anthropogenic consequences of energy consumption in Sub-Saharan Africa: is there a role for education? Environ. Chall. 5, 100234. https://doi.org/10.1016/j.envc.2021.100234.

Ben Jebli, M., Ben Youssef, S., Apergis, N., 2019. The dynamic linkage between renewable energy, tourism, CO2 emissions, economic growth, foreign direct investment, and trade. Lat. Am. Econ. Rev. 28 (1), 2. https://doi.org/10.1186/s40503-019-0063-7.

Ben Jebli, M., Farhani, S., Guesmi, K., 2020. Renewable energy, CO2 emissions and value added: empirical evidence from countries with different income levels. Struct. Chang. Econ. Dyn. 53, 402–410. https://doi.org/10.1016/j.strueco.2019.12.009.

Blundell, R., Bond, S., 1998. Initial conditions and moment restrictions in dynamic panel data models. J. Econom. 87 (1), 115–143. https://doi.org/10.1016/S0304-4076(98)00009-8.

BP, 2022. BP energy outlook 2022. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2022.pdf.

Brelsford, C., Martin, T., Hand, J., Bettencourt, L.M.A, 2018. Toward cities without slums: topology and the spatial evolution of neighborhoods. Sci. Adv. 4 (8), eaar4644. https://doi.org/10.1126/sciadv.aar4644.

Churkina, G., 2016. The role of urbanization in the global carbon cycle. Front. Ecol. Evol. 3. https://doi.org/10.3389/fevo.2015.00144.

Copeland, B.R., 2008. The pollution haven hypothesis. In: Handbook on Trade and the Environment, 2, pp. 60–70.

Creutzig, F., Baiocchi, G., Bierkandt, R., Pichler, P.-P., Seto, K.C., 2015. Global typology of urban energy use and potentials for an urbanization mitigation wedge. Proc. Natl. Acad. Sci. 112 (20), 6283–6288. https://doi.org/10.1073/pnas.1315545112.

Das, A., Sethi, N., 2023. Modelling the environmental pollution-institutional quality nexus in low- and middle-income countries: exploring the role of financial development and educational level. Environ. Dev. Sustain. 25 (2), 1492–1518. https://doi.org/10.1007/s10668-021-02105-5.

Dasgupta, S., Laplante, B., Wang, H., Wheeler, D., 2002. Confronting the environmental Kuznets curve. J. Econ. Perspect. 16 (1), 147–168. https://doi.org/10.1257/0895330027157.

Diamantopoulos, A., Schlegelmilch, B.B., Sinkovics, R.R., Bohlen, G.M., 2003. Can socio-demographics still play a role in profiling green consumers? A review of the evidence and an empirical investigation. J. Bus. Res. 56 (6), 465–480. https://doi.org/10.1016/S0148-2963(01)00241-7.

Dilanchiev, A., Nuta, F., Khan, I., Khan, H., 2023. Urbanization, renewable energy production, and carbon dioxide emission in BSEC member states: implications for climate change mitigation and energy markets. Environ. Sci. Pollut. Res. 30 (25), 67338–67350. https://doi.org/10.1007/s11356-023-27221-9.

Ehigiamusoe, K.U., Dogan, E., 2022. The role of interaction effect between renewable energy consumption and real income in carbon emissions: evidence from low-income countries. Renew. Sustain. Energy Rev. 154, 111883. https://doi.org/10.1016/j.rser.2021.111883.

Espoir, D.K., Sunge, R., 2021. Co2 emissions and economic development in Africa: evidence from a dynamic spatial panel model. J. Environ. Manag. 300, 113617. https://doi.org/10.1016/j.jenvman.2021.113617.

Farzin, Y.H., Bond, C.A., 2006. Democracy and environmental quality. J. Dev. Econ. 81 (1), 213–235. https://doi.org/10.1016/j.jdeveco.2005.04.003.

Fatima, T., Shahzad, U., Cui, L., 2021. Renewable and nonrenewable energy consumption, trade and CO2 emissions in high emitter countries: does the income level matter? J. Environ. Plan. Manag. 64 (7), 1227–1251. https://doi.org/10.1080/09640568.2020.1816532.

Fowlie, M., Meeks, R., 2021. The economics of energy efficiency in developing countries. Rev. Environ. Econ. Policy. 15 (2), 238–260. https://doi.org/10.1086/715606.

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I.T., Olsen, A., Peters, G.P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J.G., Ciais, P., Jackson, R.B., Alin, S.R., Alkama, R., Zheng, B., 2022. Global carbon budget 2022. Earth. Syst. Sci. Data 14 (11), 4811–4900. https://doi.org/10.5194/essd-14-4811-2022.

Furkan, H.B., Rakibul Hasan, K.M., Uddin, M.J., 2023. Greenhouse gas emission, GDP, tertiary education, and rule of law: a comparative study between high-income and lower-middle income countries. Heliyon 9 (6), e16265. https://doi.org/10.1016/j.heliyon.2023.e16265.

Galinato, G.I., Galinato, S.P., 2016. The effects of government spending on deforestation due to agricultural land expansion and CO2 related emissions. Ecol. Econ. 122, 43–53. https://doi.org/10.1016/j.ecolecon.2015.10.025.

Gierałtowska, U., Asyngier, R., Nakonieczny, J., Salahodjaev, R., 2022. Renewable energy, urbanization, and CO2 emissions: a global test. Energies (Basel) 15 (9). https://doi.org/10.3390/en15093390. Article 9.

Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment*. Q. J. Econ. 110 (2), 353–377. https://doi.org/10.2307/2118443.

Haldar, A., Sethi, N., 2021. Effect of institutional quality and renewable energy consumption on CO2 emissions−an empirical investigation for developing countries. Environ. Sci. Pollut. Res. 28 (12), 15485–15503. https://doi.org/10.1007/s11356-020-11532-2.

Halkos, G.E., Paizanos, E.A., 2013. The effect of government expenditure on the environment:an empirical investigation. Ecol. Econ. 91, 48–56. https://doi.org/10.1016/j.ecolecon.2013.04.002.

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environ. Sci. Technol. 43 (16), 6414–6420. https://doi.org/10.1021/es803496a.

Hua, Y., Xie, R., Su, Y., 2018. Fiscal spending and air pollution in Chinese cities: identifying composition and technique effects. China Econ. Rev. 47, 156–169. https://doi.org/10.1016/j.chieco.2017.09.007.

Huang, Y., Kuldasheva, Z., Salahodjaev, R., 2021. Renewable energy and CO2 emissions: empirical evidence from major energy-consuming countries. Energies (Basel) 14 (22), 7504. https://doi.org/10.3390/en14227504.

Hubacek, K., Baiocchi, G., Feng, K., Patwardhan, A., 2017. Poverty eradication in a carbon constrained world. Nat. Commun. 8 (1), 912. https://doi.org/10.1038/s41467-017-00919-4.

Intergovernmental Panel on Climate Change (IPCC), 2023. Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157926.

International Energy Agency (IEA), 2025. Global energy review 2025: CO_2 emissions. https://www.iea.org/reports/global-energy-review-2025/co2-emissions.

Justice, G., Nyantakyi, G., Isaac, S.H., 2024. The effect of renewable energy on carbon emissions through globalization. Heliyon 10 (5), e26894. https://doi.org/10.1016/j.heliyon.2024.e26894.

Khan, H., Weili, L., Khan, I., Khamphengxay, S., 2021. Renewable energy consumption, trade openness, and environmental degradation: a panel data analysis of developing and developed countries. Math. Probl. Eng. 2021, 1–13. https://doi.org/10.1155/2021/6691046.

Khan, I., Han, L., Khan, H., 2022. Renewable energy consumption and local environmental effects for economic growth and carbon emission: evidence from global income countries. Environ. Sci. Pollut. Res. 29 (9), 13071–13088. https://doi.org/10.1007/s11356-021-16651-y.

Kinda, S.R., 2011. Democratic Institutions and environmental quality: effects and transmission channels. https://www.econstor.eu/handle/10419/48347.

Knight, K.W., Rosa, E.A., 2011. The environmental efficiency of well-being: a cross-national analysis. Soc. Sci. Res. 40 (3), 931–949. https://doi.org/10.1016/j.ssresearch.2010.11.002.

Leach, G., 1992. The energy transition. Energy Policy 20 (2), 116–123. https://doi.org/10.1016/0301-4215(92)90105-B.

Li, Y., Zheng, Z., Zhao, M., Liu, Z., 2024. How does digital trade impact urban carbon emissions efficiency? Evidence from China's cross-border e-commerce pilot zones. J. Clean. Prod. 456, 142363. https://doi.org/10.1016/j.jclepro.2024.142363.

Lim, E., Arita, S., Joung, S., 2019. Advancing sustainable consumption in Korea and Japan—from re-orientation of consumer behavior to civic actions. Sustainability. 11 (23), 6683. https://doi.org/10.3390/su11236683.

Lin, B., Moubarak, M., 2014. Renewable energy consumption – economic growth nexus for China. Renew. Sustain. Energy Rev. 40, 111–117. https://doi.org/10.1016/j.rser.2014.07.128.

Litavcová, E., Chovancová, J., 2021. Economic development, CO2 emissions and energy use nexus-evidence from the Danube Region countries. Energies. (Basel) 14 (11), 3165. https://doi.org/10.3390/en14113165.

Liu, J., Bi, C., 2019. Effects of higher education levels on total factor productivity growth. Sustainability 11 (6), 1790. https://doi.org/10.3390/su11061790.

Lutz, W., Muttarak, R., Striessnig, E., 2014. Universal education is key to enhanced climate adaptation. Science (1979) 346 (6213), 1061–1062. https://doi.org/10.1126/science.1257975.

Majewski, S., Mentel, G., Dylewski, M., Salahodjaev, R., 2022. Renewable energy, agriculture and CO2 emissions: empirical evidence from the middle-income countries. Front. Energy Res. 10, 921166. https://doi.org/10.3389/fenrg.2022.921166.

Marcotullio, P.J., 2012. Scaling Urban Environmental Challenges: From Local to Global and Back. Earthscan.

Marcotullio, P.J., Hughes, S., Sarzynski, A., Pincetl, S., Sanchez Peña, L., Romero-Lankao, P., Runfola, D., Seto, K.C., 2014. Urbanization and the carbon cycle: contributions from social science. Earth's Future 2 (10), 496–514. https://doi.org/10.1002/2014EF000257.

Marcotullio, P.J., Sarzynski, A., Albrecht, J., Schulz, N., Garcia, J., 2013. The geography of global urban greenhouse gas emissions: an exploratory analysis. Clim. Change 121 (4), 621–634. https://doi.org/10.1007/s10584-013-0977-z.

Martínez-Zarzoso, I., Maruotti, A., 2011. The impact of urbanization on CO2 emissions: evidence from developing countries. Ecol. Econ. 70 (7), 1344–1353. https://doi.org/10.1016/j.ecolecon.2011.02.009.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, Ö., Yu, R., Zhou, B., 2021. Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896.

Muhammad, S., Long, X., 2021. Rule of law and CO2 emissions: a comparative analysis across 65 belt and road initiative(BRI) countries. J. Clean. Prod. 279, 123539. https://doi.org/10.1016/j.jclepro.2020.123539.

Nasir, M., Ur Rehman, F., 2011. Environmental Kuznets Curve for carbon emissions in Pakistan: an empirical investigation. Energy Policy 39 (3), 1857–1864. https://doi.org/10.1016/j.enpol.2011.01.025.

Nasrullah, N., Husnain, M.I.U., Khan, M.A., 2023. The dynamic impact of renewable energy consumption, trade, and financial development on carbon emissions in low-, middle-, and high-income countries. Environ. Sci. Pollut. Res. 30 (19), 56759–56773. https://doi.org/10.1007/s11356-023-26404-8.

Nathaniel, S.P., Adeleye, N., 2021. Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected african countries: implication for sustainability. J. Clean. Prod. 285, 125409. https://doi.org/10.1016/j.jclepro.2020.125409.

Nathaniel, S.P., Iheonu, C.O., 2019. Carbon dioxide abatement in Africa: the role of renewable and non-renewable energy consumption. Sci. Total Environ., 679, 337–345. https://doi.org/10.1016/j.scitotenv.2019.05.011.

Nickell, S., 1981. Biases in dynamic models with fixed effects. Econometrica 49 (6), 1417. https://doi.org/10.2307/1911408.

Oh, J., 2023. The effects of local government expenditures on carbon dioxide emissions: evidence from Republic of Korea. Sustainability 15 (20), 14913. https://doi.org/10.3390/su152014913.

Omri, A., Nguyen, D.K., Rault, C., 2014. Causal interactions between CO2 emissions, FDI, and economic growth: evidence from dynamic simultaneous-equation models. Econ. Model. 42, 382–389. https://doi.org/10.1016/j.econmod.2014.07.026.

Organisation for Economic Co-operation and Development (OECD), 2024. Inventory of Support Measures for Fossil Fuels 2024. https://www.oecd.org/en/topics/fossil-fuel-support.html.

Pachauri, S., Spreng, D., 2011. Measuring and monitoring energy poverty. Energy Policy 39 (12), 7497–7504. https://doi.org/10.1016/j.enpol.2011.07.008.

Panayotou, T., 1997. Demystifying the environmental Kuznets curve: turning a black box into a policy tool. Environ. Dev. Econ. 2 (4), 465–484. https://doi.org/10.1017/S1355770X97000259.

Petrović-Ranđelović, M., Mitić, Petar, Zdravković, A., Cvetanović, D., Cvetanović, S., 2020. Economic growth and carbon emissions: evidence from CIVETS countries. Appl. Econ. 52 (16), 1806–1815. https://doi.org/10.1080/00036846.2019.1679343.

Ponce de Leon Barido, D., Marshall, J.D., 2014. Relationship between urbanization and CO2 emissions depends on income level and policy. Environ. Sci. Technol. 48 (7), 3632–3639. https://doi.org/10.1021/es405117n.

Pradhan, P., Behera, P., Sethi, L., Rath, B.N., Sethi, N., 2025. Can green growth and ecological footprint mitigation go hand on hand? The role of sectoral energy consumption, green innovation, and greenfield investment in emerging economies. Econ. Change Restruct. 58 (2), 18. https://doi.org/10.1007/s10644-025-09860-9.

R. Alaganthiran, J., Anaba, M.I, 2022. The effects of economic growth on carbon dioxide emissions in selected Sub-Saharan African (SSA) countries. Heliyon. 8 (11), e11193. https://doi.org/10.1016/j.heliyon.2022.e11193.

Rahman, M.M., Alam, K., 2022. CO2 Emissions in Asia–Pacific region: do energy use, economic growth, financial development, and international trade have detrimental effects? Sustainability 14 (9). https://doi.org/10.3390/su14095420. Article 9.

Rahman, M.R., 2024. The effect of trade development on fossil fuel consumption in South Asian countries. Energy Res. Lett. 5 (1). https://doi.org/10.46557/001c.84456.

Roodman, D., 2009. How to do Xtabond2: an introduction to difference and system GMM in Stata. Stata J.: Promot. Commun. Stat. Stata 9 (1), 86–136. https://doi.org/10.1177/1536867X0900900106.

Rosa, E.A., Dietz, T., 2012. Human drivers of national greenhouse-gas emissions. Nat. Clim. Change 2 (8), 581–586. https://doi.org/10.1038/nclimate1506.

Sahoo, M., Sethi, N., Angel Esquivias Padilla, M., 2023. Unpacking the dynamics of information and communication technology, control of corruption and sustainability in green development in developing economies: new evidence. Renew. Energy 216, 119088. https://doi.org/10.1016/j.renene.2023.119088.

Sarkodie, S.A., Strezov, V., 2019. Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. Sci. Total Environ. 646, 862–871. https://doi.org/10.1016/j.scitotenv.2018.07.365.

Schultz, T.W., 1961. Investment in Human capital. Am. Econ. Rev. 51 (1), 1–17.

Shahbaz, M., Raghutla, C., Song, M., Zameer, H., Jiao, Z., 2020. Public-private partnerships investment in energy as new determinant of CO2 emissions: the role of technological innovations in China. Energy Econ. 86, 104664. https://doi.org/10.1016/j.eneco.2020.104664.

Sarao, J., 2020. Reducing carbon emissions will benefit the global economy. https://earth.org/carbon-emissions-economy/.

Sethi, L., Pata, U.K., Behera, B., Sahoo, M., Sethi, N., 2025. Sustainable future orientation for BRICS+ nations: green growth, political stability, renewable energy and technology for ecological footprint mitigation. Renew. Energy 244, 122701. https://doi.org/10.1016/j.renene.2025.122701.

Sethi, L., Behera, B., Sethi, N., 2024. Do green finance, green technology innovation, and institutional quality help achieve environmental sustainability? Evidence from the developing economies. Sustain. Dev. 32 (3), 2709–2723. https://doi.org/10.1002/sd.2811.

Shahsavar, T., Kubeš, V., Baran, D., 2020. Willingness to pay for eco-friendly furniture based on demographic factors. J. Clean. Prod. 250, 119466. https://doi.org/10.1016/j.jclepro.2019.119466.

Shanthini, R., 2012. Is the economic growth in the United States influenced by its fossil fuel-based carbon dioxide emissions? J. Sustain. Dev. 5 (3), p59. https://doi.org/10.5539/jsd.v5n3p59.

Sidek, N.Z.M., 2024. The role of education in reducing environmental pollution: a review. Int. J. Mod. Educ. (IJMOE) 6 (22). Article 22. https://gaexcellence.com/ijmoe/article/view/4228.

Silva, D.C., Noriller, R.M., Arakaki, K.K., Silva, J.P.da, 2022. Determinants of Co2 emission in Mercosur: the rule of investment in education. Rev. Bras. Gest. Desenvolv. Reg. 18 (1). https://doi.org/10.54399/rbgdr.v18i1.5391. Article 1.

Singh, S., Kennedy, C., 2015. Estimating future energy use and CO2 emissions of the world's cities. Environ. Pollut. 203, 271–278. https://doi.org/10.1016/j.envpol.2015.03.039.

Sohag, K., Al Mamun, M., Uddin, G.S., Ahmed, A.M., 2017. Sectoral output, energy use, and CO2 emission in middle-income countries. Environ. Sci. Pollut. Res. 24 (10), 9754–9764. https://doi.org/10.1007/s11356-017-8599-z.

Somoye, O.A., Akinwande, T.S., 2024. Exploring the association between the female gender, education expenditure, renewable energy consumption and CO2 emissions: empirical evidence from Nigeria. OPEC Energy Rev. 48 (4), 216–228. https://doi.org/10.1111/opec.12305.

Sovacool, B.K., 2016. How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Res. Soc. Sci. 13, 202–215. https://doi.org/10.1016/j.erss.2015.12.020.

Stern, D.I., 2017. The environmental Kuznets curve after 25 years. J. Bioecon. 19 (1), 7–28. https://doi.org/10.1007/s10818-017-9243-1.

Szetela, B., Majewska, A., Jamroz, P., Djalilov, B., Salahodjaev, R., 2022. Renewable energy and CO2 emissions in top natural resource rents depending countries: the role of governance. Front. Energy Res. 10, 872941. https://doi.org/10.3389/fenrg.2022.872941.

Tawiah, V., Zakari, A., Adedoyin, F.F., 2021. Determinants of green growth in developed and developing countries. Environ. Sci. Pollut. Res. 28 (29), 39227–39242. https://doi.org/10.1007/s11356-021-13429-0.

Ünal, E., Lin, B., Managi, S., 2023. CO2 emissions embodied in bilateral trade in China: an input-output analysis. Environ. Impact. Assess. Rev. 103, 107218. https://doi.org/10.1016/j.eiar.2023.107218.

Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28 (12), 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7.

Wan, G., Wang, C., Wang, J., Zhang, X., 2022. The income inequality-CO2 emissions nexus: transmission mechanisms. Ecol. Econ. 195, 107360. https://doi.org/10.1016/j.ecolecon.2022.107360.

Wang, J., Jiang, C., Li, M., Zhang, S., Zhang, X., 2023. Renewable energy, agriculture, and carbon dioxide emissions nexus: implications for sustainable development in sub-Saharan African countries. Sustain. Environ. Res. 33 (1), 31. https://doi.org/10.1186/s42834-023-00193-8.

Wang, Q., Zhang, F., 2021. The effects of trade openness on decoupling carbon emissions from economic growth – evidence from 182 countries. J. Clean. Prod. 279, 123838. https://doi.org/10.1016/j.jclepro.2020.123838.

Wang, Q., Zhang, F., Li, R., 2024. Free trade and carbon emissions revisited: the asymmetric impacts of trade diversification and trade openness. Sustain. Dev. 32 (1), 876–901. https://doi.org/10.1002/sd.2703.

Wawrzyniak, D., Doryń, W., 2020. Does the quality of institutions modify the economic growth-carbon dioxide emissions nexus? Evidence from a group of emerging and developing countries. Econ. Res.-Ekon. Istraž. 33 (1), 124–144. https://doi.org/10.1080/1331677X.2019.1708770.

WDI. (2025). World Development Indicators. World Bank. https://databank.worldbank.org/source/world-development-indicators—Google Search. (n.d.). Retrieved April 11, 2025, from https://www.google.com/search?q=WDI.+(2022).+World+Development+Indicators.+World+Bank.https%3A%2F%2Fdatabank.worldbank.org%2Fsource%2Fworld-development-indicators&oq=WDI.+(2022).+World+Development+Indicators.+World+Bank.https%3A%2F%2Fdatabank.worldbank.org%2Fsource%2Fworld-development-indicators&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIGCAEQRRg80gEJMzg0N2owajE1qAIIsAIB8QWC2u6QKCBW4g&sourceid=chrome&ie=UTF-8.

Xu, P., Zhang, J., Mehmood, U., 2023a. How do green investments, foreign Direct investment, and renewable energy impact CO2 emissions? Measuring the role of education in E-7 nations. Sustainability 15 (19). https://doi.org/10.3390/su151914052. Article 19.

Xu, X., Dai, W., Muhammad, T., Zhang, T., 2023b. The dynamic relationship between carbon emissions, financial development, and renewable energy: a study of the N-5 asian countries. Sustainability 15 (18), 13888. https://doi.org/10.3390/su151813888.

Yuan, R., Masron, T.A., Chen, Y., Azman, N.S., 2025. Government effectiveness on environmental degradation in developing countries. Int. J. Environ. Sci. Technol. https://doi.org/10.1007/s13762-025-06560-9.

Zheng, Y., Shan, R., Xu, W., Qiu, Y., 2024. Effectiveness of carbon dioxide emission target is linked to country ambition and education level. Commun. Earth Environ. 5 (1), 209. https://doi.org/10.1038/s43247-024-01373-z.

Zhou, R., Guan, S., He, B., 2025. The impact of trade openness on carbon emissions: empirical evidence from emerging countries. Energies (Basel) 18 (3), 697. https://doi.org/10.3390/en18030697.

Zugravu-Soilita, N., 2018. The impact of trade in environmental goods on pollution: what are we learning from the transition economies' experience? Environ. Econ. Policy Stud. 20 (4), 785–827. https://doi.org/10.1007/s10018-018-0215-z.

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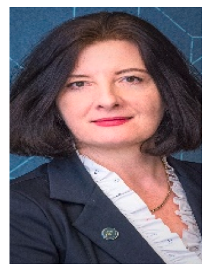

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