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Balancing growth and sustainability: The role of women's empowerment, innovation, and green transitions



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ABSTRACT

Climate change and environmental degradation remain urgent global challenges driven by rapid economic growth, fossil fuel dependence, and unsustainable consumption. While prior studies have explored the roles of technology, energy, and growth, limited research examines how women's empowerment shapes the economy–energy–technology–environment nexus. This study investigates the joint impact of economic development, technological innovation, renewable energy, and women's empowerment on environmental sustainability using data from 189 countries spanning 1990–2022. The Autoregressive Distributed Lag (ARDL) model is employed to assess both short- and long-run dynamics, with robustness verified through Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegration Regression (CCR). Results show that economic growth intensifies greenhouse gas (GHG) emissions, while technological innovation, renewable energy use, and women's empowerment significantly reduce emissions across time horizons. These findings underscore the need to integrate gender equity with technological and energy transitions to decouple economic progress from ecological degradation. Policy recommendations include expanding renewable energy, incentivizing green technologies, and strengthening women's participation in economic and political decision-making. By positioning gender empowerment as a structural driver of sustainability, this study advances an inclusive framework for achieving a resilient, low-carbon global future.

1. Introduction

Environmental sustainability has emerged as one of the defining challenges of the twenty-first century (Akinyele et al., 2025; Khanna et al., 2025). Accelerating climate change, biodiversity loss, and resource depletion have intensified global concern over how economic and technological progress can coexist with ecological integrity (Eelager et al., 2025). Rapid industrialization and economic expansion have undeniably elevated global living standards, yet they have simultaneously heightened environmental degradation through excessive GHG emissions, fossil fuel dependence, and unsustainable production

practices (Ali et al., 2025). As global economies grapple with these dual imperatives, scholars and policymakers increasingly recognize that sustainability requires more than technological advancement—it also demands structural and social transformation, particularly in the realms of equity and inclusion (Cerchione et al., 2025).

Despite decades of environmental initiatives, GHG emissions continue to rise, revealing the inadequacy of approaches that address technological or economic factors in isolation (Glavina et al., 2025). Existing policy frameworks often neglect the human and institutional dimensions that shape ecological outcomes (Chapagain et al., 2025). Among these, women's empowerment stands out as an underexplored

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yet potentially transformative factor. Women play pivotal roles in influencing household energy use, sustainable consumption, entrepreneurship, and environmental governance (Sen et al., 2025). Empowered women not only contribute to economic productivity but also drive social awareness and sustainable decision-making, suggesting that gender equality may serve as a critical lever in global environmental transitions (Elbushra et al., 2025). However, this dimension remains marginal in mainstream sustainability discourse, creating a significant knowledge gap regarding how women's empowerment interacts with economic and technological drivers to shape environmental outcomes (Cellini et al., 2025; Gbolonyo et al., 2025).

While prior research has examined the impact of economic growth, technological innovation, or renewable energy adoption on environmental sustainability independently (Alola & Adebayo, 2023; Iqbal et al., 2024; Lu et al., 2025; Raihan & Tuspekova, 2023; Zhang et al., 2025), studies integrating these economic and technological dimensions with women's empowerment remain scarce. The majority of existing gender–environment studies are limited to specific countries or regions, rely on cross-sectional data, or fail to assess long-term global dynamics (Achoo et al., 2022; Jiang & Akbar, 2018; Li et al., 2024; Lv & Deng, 2019; Saleh & Maigoshi, 2025). Consequently, the broader global interplay among economic growth, innovation, renewable energy, and women's empowerment remains empirically under-investigated. Addressing this gap is critical for achieving multiple Sustainable Development Goals (SDGs)—notably SDG 5 (gender equality), SDG 7 (affordable and clean energy), and SDG 13 (climate action)—which collectively emphasize inclusive, innovative, and low-carbon development pathways.

To address these shortcomings, the present study investigates the combined and individual effects of economic development, technological innovation, renewable energy use, and women's empowerment on environmental sustainability. Using data from 189 countries spanning 1990–2022, the study employs the ARDL model alongside robustness tests using the FMOLS, DOLS, and CCR methods. This comprehensive methodological approach enables the examination of both short-run and long-run relationships, ensuring that the results are statistically rigorous and globally generalized.

The study seeks to answer the following research questions: (1) How does economic growth influence environmental sustainability across countries and over time? (2) To what extent does technological innovation mitigate or exacerbate environmental degradation? (3) What role does renewable energy consumption play in promoting global ecological resilience? (4) How does women's empowerment interact with economic and technological factors to influence environmental outcomes? (5) What are the combined effects of these four variables in shaping sustainable development trajectories worldwide?

By addressing these questions, the study contributes to the literature in several important ways. First, it fills a critical research gap by integrating women's empowerment into the economy–energy–technology–environment (EETE) nexus, a dimension that has been largely overlooked in prior global analyses. Second, it provides robust empirical evidence covering 189 countries over three decades, offering the most comprehensive cross-country assessment of these relationships to date. Third, it advances methodological rigor by combining ARDL with FMOLS, DOLS, and CCR to ensure robustness across both temporal and structural variations. Finally, it introduces a policy-relevant framework that connects gender equity, technological innovation, and renewable energy as mutually reinforcing drivers of sustainable development.

The novelty of this study lies in its interdisciplinary and global approach. By conceptualizing women's empowerment not merely as a social outcome but as a structural determinant of environmental quality, it challenges conventional paradigms that treat gender as peripheral to environmental discourse. The findings contribute to a growing recognition that sustainability is inherently inclusive—requiring technological and economic progress that is equitably shared and socially

grounded. Ultimately, this study underscores that aligning economic expansion with innovation, renewable energy, and gender equality represents not just an environmental imperative but a holistic pathway toward a resilient, low-carbon global future.

2. Literature review

2.1. Environmental sustainability

GHG emissions resulting from intensified fossil fuel use and deforestation exacerbate global warming and climate change, leading to profound impacts on human health, ecosystems, and sea-level rise (Filonchik et al., 2024; Raihan, 2023a). Environmental sustainability, conversely, refers to the capacity to preserve natural systems while ensuring that future generations can access essential resources (Montefalcone et al., 2025). Achieving sustainability requires reducing emissions through the development of low-carbon societies, expansion of renewable energy, advancement of green technologies, and improvements in energy efficiency (Eelager et al., 2025; Lu et al., 2025; Raihan et al., 2023; Reddy et al., 2024).

Recent studies typically measure environmental sustainability using indicators such as CO₂ emissions (Ahmed et al., 2025; Bennaceur et al., 2025; Bergougui, 2024; Khan et al., 2024; Mehmood et al., 2023; Pak-rooh et al., 2025; Raihan et al., 2022; Xu et al., 2025) and GHG emissions (Chien et al., 2022; Hassan et al., 2024; Khan et al., 2025; Raihan et al., 2025; Usman et al., 2023). Alternative measures, including the ecological footprint (Abdullahi et al., 2025; Nketiah et al., 2024; Raza et al., 2023; Rout et al., 2022; Ullah et al., 2025; Waaje et al., 2025; Wang et al., 2025; Yasin et al., 2025) and the load capacity factor (Bergougui & Meziane, 2025; Jahanger et al., 2024; Liu et al., 2022; Pata & Pata, 2025; Usman et al., 2025; Zhao et al., 2023), have also been employed to capture broader ecological dynamics.

2.2. Economy and environment

A large empirical literature documents a positive linkage between economic expansion and environmental pressure, particularly GHG emissions. Country and multi-country studies using ARDL-family and panel estimators consistently show that GDP growth raises emissions in both short- and long-run horizons (e.g., Korea, South Asia, Mercosur, and emerging economies), with some work also noting an EKC-type nonlinearity at higher income levels (Behera et al., 2024a; Chien et al., 2022; Hassan et al., 2024; Kim, 2020; Raihan, 2023b; Sahoo et al., 2023; Tariq et al., 2022; Usman et al., 2023).

Recent evidence refines this picture along three fronts. First, scope and heterogeneity: sector-level analyses for OECD economies show that EKC dynamics are not uniform across sectors, cautioning against blanket inferences from aggregate data (Muratoğlu et al., 2024). Second, policy mediation: global panels (≈ 191 countries, 1989–2022) suggest a policy-contingent EKC, where stricter climate policy shifts the income–emissions relationship, lowering the turning point ($\approx \$25k$ per-capita on average) and dampening growth-driven emissions (Bettarelli et al., 2025). Third, composition and structural change: cross-bloc evidence (BRICS + vs. advanced economies) indicates that urbanization and energy structure co-evolve with growth, shaping emissions trajectories and the feasibility of decoupling (Albanese et al., 2025).

At the same time, mixed EKC validity continues to surface in 2024–2025 studies. Some find that higher growth persistently elevates pollution—contradicting the EKC in certain samples or income ranges—while others report model-dependent results across country groups (e.g., E7) and specifications, underscoring context-dependence in the growth–emissions nexus (Ayık & Özer, 2025; Guliyev & Seyfullayev, 2025; Ridwan et al., 2024). Taken together, the emerging consensus is not that growth automatically cleans the environment, but that institutions, sectoral structure, and energy mix determine whether growth is coupled—or decoupled—from emissions.

Finally, contemporaneous assessments of the global carbon budget and peak-emissions outlook reinforce the urgency of coupling growth with rapid energy transition. Near-term projections warn of record fossil CO₂ in 2025 and a narrowing window to stay near 1.5 °C, implying that growth strategies that rely on fossil inputs will intensify climate risk absent accelerated deployment of clean energy and stronger climate policy.

2.3. Technological innovation and environment

Technological innovation is increasingly positioned as a structural lever for decarbonization because it can lower energy intensity, substitute cleaner production processes for legacy methods, and diffuse environmental management practices across sectors (Sovacool, 2025; Younes et al., 2025). Empirical studies consistently associate stronger innovation performance with lower emissions when innovation is oriented toward environmental objectives. For instance, cross-country and regional analyses indicate that growth in environmental patents, cleaner production technologies, and ICT-enabled efficiency improvements is linked to declines in GHG or carbon indicators (Adebayo et al., 2024; Alola & Adebayo, 2023; Khanna et al., 2025; Miśkiewicz, 2021; Wenlong et al., 2023; Yin et al., 2025). Recent work further strengthens this conclusion: panel and quantile approaches show that environment-related technologies and innovation capabilities reduce GHG emissions and ecological pressure across heterogeneous development contexts (Aydin et al., 2024; Hassan et al., 2024; Khan et al., 2025; Luo et al., 2025; Ou et al., 2025; Sun & Qamruzzaman, 2025). Within emerging and large economies, green innovation has been shown to curb ecological footprint and carbon intensity when embedded in supportive policy and market environments, underscoring the importance of aligning innovation systems with climate objectives (Behera et al., 2024b; Gan, 2025; Han, Peng, et al., 2025; Hardi et al., 2025; Hassan et al., 2025; Yuran & Anwar, 2025).

At the same time, the literature cautions that innovation is not universally benign. Evidence of rebound and composition effects suggests that technology can, under certain conditions, raise energy demand or shift activity toward polluting segments, partially offsetting efficiency gains (Özsoy, 2024). In several developing-country samples, nominally “green” technology indicators have coincided with higher emissions, a result attributed to energy-intensive diffusion stages, weak regulation, and lock-in to fossil-based infrastructures (Bergougui et al., 2025; Sethi, Behera, & Sethi, 2024; Younes et al., 2025). These mixed findings highlight that innovation’s net environmental effect depends on the directionality of R&D, complementary investments (e.g., renewables and storage), and institutions capable of pricing externalities and accelerating clean adoption.

Studies documenting the interplay of innovation with renewable deployment, financial and institutional quality, and trade show that green R&D and technology diffusion reduce ecological footprint and GHGs when supported by stable governance and targeted financing (Jahanger et al., 2024; Raza et al., 2023; Xinyu et al., 2025; Zhang et al., 2025). In emerging and BRICS settings, green technology combined with political stability and green finance is repeatedly associated with footprint mitigation and pathways toward carbon neutrality (Behera et al., 2025; Pradhan et al., 2025; Sethi et al., 2025). Likewise, analyses of Asian and G-20 economies report that innovation—especially when coupled with institutional quality—advances environmental and economic sustainability, helping to decouple growth from emissions (Khanna et al., 2025; Wahab et al., 2024; Zhang et al., 2025). Collectively, the evidence suggests that innovation’s effectiveness is amplified by policy coherence: carbon pricing, standards that steer R&D toward low-carbon technologies, and diffusion mechanisms that accelerate commercialization in high-emitting sectors.

Taken together, the literature indicates that technological innovation contributes materially to emissions abatement when it is mission-oriented, scaled, and embedded within enabling energy and regulatory

systems. Where innovation is narrowly cost- or output-oriented, or where governance gaps impede clean diffusion, rebound and transitional frictions can weaken or reverse environmental gains. The weight of recent global evidence, however, favors the view that targeted green innovation—measured through patents, clean technology deployment, and ICT-enabled efficiencies—lowers GHG emissions and ecological pressures over the medium to long run, particularly when paired with renewable energy transitions and robust institutions.

2.4. Green energy and environment

The transition to green energy has emerged as a cornerstone of global strategies aimed at mitigating climate change and advancing environmental sustainability. Empirical evidence consistently demonstrates that renewable energy consumption significantly reduces GHG emissions in both the short and long term. Early studies by Kim (2020) and Chien et al. (2022) established this inverse relationship in Asian and OECD contexts, showing that renewable energy adoption improves air quality and decarbonizes production systems. Subsequent analyses extended this evidence using advanced econometric approaches such as the ARDL, FMOLS, and DOLS, confirming that green energy not only curtails emissions but also supports long-term ecological resilience (Fatima et al., 2024; Haloui et al., 2025; Satrovic et al., 2025).

Recent investigations have deepened these insights, highlighting both the scale and scope of renewable energy’s environmental benefits. For instance, Justice et al. (2024), Matenda et al. (2024), Kishore et al. (2025), Rai et al. (2025), Shekhawat et al. (2025), and Yousaf et al. (2025) found that renewable energy consumption in emerging economies leads to substantial declines in CO₂ emissions, while Hassan et al. (2024), Benhacene and Hussien (2025), Yao et al. (2025), and Yin et al. (2025) reported that sustainable energy contributes to environmental, financial, and social well-being. Multi-country evidence from Behera et al. (2024d), Wang et al. (2024), Al-Zubairi et al. (2025), and Han, Peng, et al. (2025) further reveals that renewable energy deployment exerts strong positive externalities by lowering pollution and fostering economic diversification, especially when accompanied by political stability and technological innovation. These results are corroborated by studies such as Azimi et al. (2025), Gan (2025), Iqbal et al. (2025), and Rafiq et al. (2025), which identifies renewable energy and institutional quality as mutually reinforcing drivers of sustainability, and by Behera et al. (2025), who emphasize renewable energy’s catalytic role in achieving carbon neutrality through its interaction with green growth and ICT development.

A growing body of research also underscores the regional heterogeneity in renewable energy outcomes. In resource-rich economies, renewable deployment alleviates ecological pressure by moderating dependence on fossil fuels and improving the environmental quality (Almulhim et al., 2025; Faizi et al., 2025; Hassan et al., 2025; Zhu et al., 2025). Similarly, cross-regional analyses by Benhacene and Hussien (2025), Maghyereh et al. (2025), Michailidis et al. (2025), Pata et al. (2025), and Usman et al. (2025) highlight that investments in solar, wind, and hydropower not only mitigate emissions but also enhance sustainable development indices, reflecting the broad environmental dividends of clean energy transitions.

Beyond direct emission reductions, the expansion of renewable energy supports multiple sustainability co-benefits. It strengthens energy security, reduces exposure to volatile fossil fuel markets, and stimulates innovation within the green technology sector (Dhayal, Agrawal, Agrawal, Kumar, & Giri, 2024; Elkhatat & Al-Muhtaseb, 2024). Studies such as Reddy et al. (2024) and Wang et al. (2025) demonstrate that integrating renewables into industrial and building systems yields efficiency gains and lowers ecological footprints. These advances align with international efforts to achieve the SDGs, particularly SDG 7 (affordable and clean energy) and SDG 13 (climate action), through the decarbonization of economic activities and promotion of inclusive green growth.

However, despite these gains, the transition remains uneven across

regions due to infrastructural, financial, and institutional constraints. Chen et al. (2024), Sethi, Behera, Behera, and Sethi (2024), Behera et al. (2025), and Mamat et al. (2025) note that in developing economies, limited access to green finance, inadequate grid infrastructure, and weak regulatory frameworks often hinder the large-scale adoption of renewable energy. Addressing these barriers requires targeted policy interventions such as subsidies for renewable technologies, investment in grid modernization, and the creation of dedicated green energy institutions capable of coordinating sustainable development agendas.

Overall, the cumulative evidence reaffirms that renewable energy adoption is central to global emission reduction efforts. When combined with innovation, institutional quality, and gender-inclusive governance, green energy accelerates progress toward carbon neutrality and ecological resilience. The environmental and socioeconomic benefits of renewable energy extend beyond decarbonization—they also reshape energy systems to be more equitable, resilient, and adaptive to the challenges of climate change. As nations approach mid-century decarbonization milestones, expanding renewable energy capacity remains not merely an environmental priority but a strategic imperative for sustainable global development.

2.5. Women's empowerment and environment

The interlinkages between women's empowerment and environmental sustainability have gained renewed scholarly and policy attention, particularly in the context of the SDGs. Recent evidence reinforces that women's empowerment is not merely a social equity objective but a structural determinant of ecological outcomes (Dwipayanti et al., 2025; Gbolonyo et al., 2025). Empowered women influence environmental sustainability through multiple channels—ranging from household energy use and consumption patterns to participation in environmental governance, entrepreneurship, and innovation (Gozgor et al., 2025; Raman et al., 2025; Salamzadeh et al., 2025). The growing literature emphasizes that gender-inclusive governance enhances environmental performance by promoting the adoption of cleaner energy, climate adaptation strategies, and sustainable livelihood practices (Elbushra et al., 2025; Gbolonyo et al., 2025; Ko & Leung, 2025; Sen et al., 2025).

Early empirical studies such as Jiang and Akbar (2018) and Lv and Deng (2019) provided foundational evidence that greater female representation in corporate and political leadership correlates with improved environmental outcomes. More recent analyses have expanded these findings to cross-country and global scales. For instance, Li et al. (2024) and Sanchez-Olmedo et al. (2025) demonstrated that gender empowerment substantially reduces global GHG emissions, while Antari et al. (2025), Babiker et al. (2025), Mnasri et al. (2025), Omenihu et al. (2025), Saleh and Maigoshi (2025), and Zhu and Chen (2025) found that gender diversity enhances firms' environmental, social, and governance (ESG) performance across regions. These studies underscore that women leaders tend to prioritize sustainability agendas, enforce environmental compliance, and foster organizational cultures of ecological responsibility.

At the community and household levels, women's empowerment significantly affects patterns of energy consumption, land use, and resource management. Evidence from Sub-Saharan Africa and South Asia indicates that women's financial inclusion and access to clean energy technologies mitigate environmental degradation by promoting sustainable consumption and reducing dependence on biomass (Langnel et al., 2021; Sen et al., 2025). Similarly, Gbolonyo et al. (2025) revealed that empowering women through renewable energy initiatives in Ghana enhances both energy access and environmental quality, demonstrating the dual dividends of gender equity and sustainability. These outcomes resonate with Thomas (2024), who argues that women entrepreneurs, especially in green enterprises, play a pivotal role in advancing low-carbon innovations and circular economy models.

In the context of innovation and environmental governance, women's participation has been shown to enhance institutional

responsiveness and technological diffusion. Le Loarne-Lemaire et al. (2021), Mujeed et al. (2021), and Wei et al. (2021) earlier documented how women's autonomy within innovation ecosystems fosters eco-friendly technological spillovers and reinforces corporate social responsibility. Recent global analyses extend this insight by demonstrating that women in research and development (R&D) drive higher innovation efficiency in climate-related technologies, particularly when institutional support and inclusive innovation systems are present (Abdulla et al., 2025; Cellini et al., 2025). The inclusion of women in climate decision-making has also been linked to the development of more socially grounded and equitable environmental policies, which strengthen collective adaptive capacity to climate change (Biswas & Barua, 2025).

Furthermore, recent studies emphasize the synergistic effects of women's empowerment with renewable energy and green innovation. Vogel et al. (2024), Fu et al. (2025), Gbolonyo et al. (2025), Gozgor et al. (2025), and Raman et al. (2025) highlight that gender-inclusive renewable energy governance enhances ecological outcomes by fostering participation, accountability, and equitable access to clean technologies. In developing contexts, women's engagement in decentralized renewable energy projects—such as solar mini-grids and biogas initiatives—has been shown to promote both environmental protection and socioeconomic resilience (Arshad et al., 2024; Raman et al., 2025; Sen et al., 2025). These findings illustrate that integrating gender equality into energy transitions produces co-benefits that extend beyond emission reduction to include community empowerment and poverty alleviation.

Recent theoretical contributions (Cellini et al., 2025; Fu et al., 2025; Gupta et al., 2024) advocate reframing women's empowerment as a systemic driver of sustainability rather than a subsidiary outcome of development. This shift recognizes that gender equity enhances institutional quality, strengthens governance, and facilitates inclusive participation in environmental policymaking. Evidence from Elbushra et al. (2025) further supports this perspective, showing that women's empowerment contributes to sustainable economic diversification and improved resource management. Similarly, studies by Saha et al. (2022), Chen (2024), and Han, Zhang, et al. (2025) suggest that the intersection of gender inclusion, information technology, and green finance accelerates the transition to sustainable production systems.

Taken together, the literature converges on a robust conclusion: women's empowerment has a statistically and substantively significant influence on environmental outcomes across multiple levels of analysis—micro, meso, and macro. It fosters the diffusion of green technologies, supports renewable energy adoption, and enhances institutional commitment to climate action. The collective evidence emphasizes that gender inclusion must be embedded in sustainability frameworks, climate finance mechanisms, and national adaptation plans to achieve long-term ecological resilience. Ultimately, advancing women's agency and participation represents not only a moral and social imperative but also a strategic pathway toward an equitable and sustainable global future.

2.6. Research gap

While substantial research confirms the independent roles of economic growth, technological innovation, renewable energy, and women's empowerment in shaping environmental sustainability, few studies explore their joint effects within a unified analytical framework. Most gender-focused studies remain region-specific, rely on cross-sectional data, and lack global generalizability. Furthermore, the long-term interactions among these variables have not been systematically examined. Consequently, a significant gap persists in understanding how women's empowerment interacts with economic and technological drivers to influence sustainability outcomes on a global scale.

This study seeks to bridge these gaps by employing advanced econometric techniques—ARDL, FMOLS, DOLS, and CCR—to examine the combined and long-run relationships among GDP growth,

technological innovation, renewable energy, and women's empowerment. By integrating these dimensions, the research aims to provide comprehensive insights into the mechanisms through which social inclusion and innovation collectively drive environmental sustainability.

3. Theoretical framework and hypothesis development

The theoretical foundation of this study lies in the nexus connecting economic growth, technological progress, renewable energy, and women's empowerment to environmental sustainability. Environmental quality is most often measured through greenhouse gas (GHG) emissions, which represent the cumulative effects of human activity on the planet's climate system. While economic development is essential for improving living standards, it is also associated with increased industrial activity, energy consumption, and resource extraction, which can contribute significantly to environmental degradation. The Environmental Kuznets Curve (EKC) hypothesis suggests that emissions may initially rise with economic growth but eventually decline once economies achieve higher levels of income and adopt cleaner technologies. However, empirical evidence remains mixed, particularly across developing and emerging nations. Based on this reasoning, the first hypothesis of this study proposes that economic growth is likely to increase GHG emissions in the short and long term unless accompanied by sustainability-focused policies.

H1. Economic growth has a positive relationship with GHG emissions, indicating that an increase in GDP expansion leads to higher environmental degradation in both the short and long term.

Technological innovation is considered a central driver of environmental sustainability. Through the development and diffusion of eco-friendly technologies, societies can improve resource efficiency, reduce waste, and substitute cleaner production processes for traditional polluting methods. Prior research shows that technological progress in sectors such as energy, manufacturing, and agriculture can reduce carbon intensity and facilitate the transition toward low-carbon development. At the same time, rebound effects—where increased efficiency leads to higher overall consumption—can offset some benefits. Given this complexity, the second hypothesis asserts that technological innovation is expected to reduce GHG emissions, particularly when innovations are oriented toward environmental objectives.

H2. Technological innovation has a negative relationship with GHG emissions, suggesting that advancements in innovation contribute to reducing environmental degradation.

Renewable energy represents a critical pathway for addressing climate change and promoting sustainability. Unlike fossil fuels, renewable sources such as wind, solar, hydro, and biomass provide low-carbon alternatives that directly mitigate emissions while supporting energy security and economic diversification. Numerous studies confirm that higher shares of renewable energy in the energy mix reduce both carbon dioxide and aggregate GHG emissions. Thus, the third hypothesis anticipates that greater adoption of renewable energy contributes to the reduction of emissions in both the short and long term, strengthening global environmental sustainability.

H3. Renewable energy consumption has a negative relationship with GHG emissions, implying that greater adoption of renewable energy sources improves environmental sustainability.

Women's empowerment is increasingly recognized as an important but often overlooked factor in the sustainability debate. Women influence environmental outcomes through multiple channels, including household energy choices, entrepreneurial activities in the green economy, and political participation in shaping environmental legislation. Research shows that empowered women tend to advocate for clean energy, support corporate social responsibility, and enhance the uptake of sustainable technologies. Their greater involvement in decision-

making positions has been linked with improved ecological policies and stronger community-level environmental stewardship. Accordingly, the fourth hypothesis of this study posits that women's empowerment plays a significant role in reducing GHG emissions and promoting ecological resilience.

H4. Women's empowerment has a negative relationship with GHG emissions, indicating that higher female participation and inclusion contribute to reducing environmental degradation.

Bringing these four elements together, the theoretical framework conceptualizes environmental sustainability as an outcome of the interplay between economic growth, technological advancement, renewable energy adoption, and women's empowerment. The empirical analysis evaluates these relationships both in the short run and long run to determine whether the hypothesized effects hold true across a diverse global sample.

4. Data and methodology

4.1. Data

To empirically test these hypotheses, the study employs a global panel dataset covering 189 countries from 1990 to 2022. This time span of 33 years provides a robust basis for examining both long- and short-term dynamics, particularly given the global rise in greenhouse gas emissions and the parallel growth of renewable energy, technological innovations, and gender empowerment initiatives over the same period. The dependent variable in the study is total GHG emissions, expressed in kilotons of carbon dioxide equivalent (CO₂eq), which includes carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and fluorinated gases such as hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. GHG emissions are considered a comprehensive measure of environmental sustainability because they capture the combined impacts of industrial, agricultural, and household activities on the climate system.

The primary independent variables are economic growth, technological innovation, renewable energy consumption, and women's empowerment. Economic growth is measured using gross domestic product (GDP) per capita in current US dollars, consistent with prior empirical literature linking economic performance to emissions. Technological innovation is captured through the number of patents filed and registered, reflecting the creation and diffusion of new technologies with potential environmental impacts. Renewable energy consumption is measured as the share of renewables in total final energy use, which directly reflects the transition toward cleaner energy sources. Women's empowerment is proxied by the female employment-to-population ratio for individuals aged 15 and above, highlighting women's participation in the labor force as a marker of agency and inclusion.

Table 1 presents variable descriptions, measurements, and data sources. All variables are obtained from the World Bank's World Development Indicators (WDI) database (World Bank, 2025), ensuring consistency and comparability across countries. The use of this standardized dataset also allows for broad generalizability of the results across developed, emerging, and developing economies. By integrating economic, technological, energy, and gender dimensions, the dataset provides a comprehensive empirical basis to investigate the theoretical framework proposed in this study.

4.2. Empirical model and analysis flowchart

The empirical framework of this study is represented by the following functional form:

$$E_t = f(Y_t, T_t, R_t, W_t) \quad (1)$$

Where E_t represents environmental quality at time t , Y_t denotes

Table 1
Variable descriptions, measurements, and data source.

Variable	Symbol	Description	Measurement/ unit	Data source
Environmental sustainability	E	Proxy for environmental quality, reflecting the total level of GHG emissions	Total GHG emissions (kilotons of CO ₂ equivalent)	World Bank (2025)
Economic growth	Y	Represents the level of economic development and production	GDP per capita (current US dollars)	
Technological innovation	T	Indicates the extent of technological advancement and innovation activity	Number of patent applications filed and registered	
Renewable energy consumption	R	Reflects the adoption of renewable energy sources within total energy use	Share of renewable energy in total final energy consumption (%)	
Women's empowerment	W	Captures gender inclusion and participation in economic activities	Female employment-to-population ratio, age 15+ (%)	

economic development, T_t captures technological innovations, R_t refers to renewable energy consumption, and W_t indicates women's empowerment. Prior to the empirical estimations, all variables are transformed into their natural logarithmic form to simplify the analysis and facilitate the interpretation of results. The econometric model is specified as follows:

$$LE_t = \beta_0 + \beta_1 LY_t + \beta_2 LT_t + \beta_3 LR_t + \beta_4 LW_t + \varepsilon_t \quad (2)$$

Where β_0 denotes the intercept and ε_t represents the error term, while β_1 , β_2 , β_3 , and β_4 are the estimated coefficients.

The analytical process is illustrated in Fig. 1. After defining the scope of the study and establishing the theoretical framework, the stationarity of the data was first assessed using unit root tests. Once the dataset was confirmed to be stationary, the analysis proceeded with the ARDL methodology, which involves two main steps. Following the confirmation of cointegration through the ARDL bounds test, both short- and long-run dynamics were examined within the ARDL framework. In addition, DOLS, FMOLS, and CCR regression techniques were employed to validate the long-run coefficients initially estimated by ARDL.

4.3. Unit root test for data stationarity

In time-series econometric analysis, establishing the stationarity properties of variables is a critical first step before applying advanced models such as the ARDL approach. A stationary series has statistical properties—mean, variance, and autocovariance—that remain constant over time. If variables are non-stationary, regression results may become spurious, leading to misleading inferences (Behera et al., 2025; Pradhan et al., 2025; Raihan, 2023c; Raihan & Tuspekova, 2022a; Sethi et al., 2025). Thus, determining whether the chosen variables are stationary at levels or become stationary after differencing is a necessary condition for reliable estimation.

To assess stationarity, this study employed three complementary unit root tests: the Augmented Dickey–Fuller (ADF) test (Dickey & Fuller, 1981), the Phillips–Perron (P-P) test (Phillips & Perron, 1988), and the Dickey–Fuller Generalized Least Squares (DF-GLS) test (Elliott et al., 1992). The ADF test is widely used in time-series analysis to detect whether a series contains a unit root, with the null hypothesis assuming non-stationarity. By augmenting the standard Dickey–Fuller framework with lagged differences of the dependent variable, the ADF test corrects

for higher-order autocorrelation, making it suitable for macroeconomic datasets such as those employed here.

The Phillips–Perron test extends this analysis by addressing heteroskedasticity and autocorrelation in the error terms without the need to add lagged difference terms explicitly. This test provides robustness to serial correlation and varying error structures, which are common in long time-series data covering multiple economies. The inclusion of the P-P test ensures that stationarity results are not biased by error dynamics that may affect the ADF outcomes.

The DF-GLS test offers an additional refinement by applying a generalized least squares (GLS) detrending procedure before testing for a unit root. This approach enhances the power of the test, particularly in small samples or when the series exhibits strong persistence. Given the relatively long but finite span of data in this study (33 years, 1990–2022), the DF-GLS test provides a valuable complement to the ADF and PP tests by improving sensitivity to subtle deviations from non-stationarity.

4.4. ARDL simulation

Following the verification of stationarity, this study proceeds to empirically estimate the relationships among the selected variables. To assess the long-run connections, the ARDL bounds testing approach of Pesaran et al. (2001) was applied, using F-statistics. When the computed F-statistic exceeds the upper bound critical value, the null hypothesis of no cointegration is rejected. This confirms the existence of a long-run equilibrium relationship among the variables and allows the use of the ARDL model to examine both short- and long-run effects on environmental quality at the global level (Hussain et al., 2023; Raihan & Bari, 2024; Shahid et al., 2024).

Several key advantages justify the choice of the ARDL framework. First, unlike alternative cointegration techniques that require large data samples, ARDL is statistically robust even in smaller samples. Second, the method does not require all regressors to be of the same order of integration, as it can be applied to variables that are either $I(0)$, $I(1)$, or a mixture of both. Third, the ARDL framework accommodates flexible lag structures, allowing it to capture dynamic relationships more effectively.

The accuracy of ARDL estimation, however, depends on the appropriate selection of lag lengths. Incorrect specification may produce biased estimates or overlook important dynamic effects. In this study, optimal lag lengths were determined using standard information criteria, including the Akaike Information Criterion (AIC), Schwarz Bayesian Criterion (SBC), and Hannan–Quinn Criterion (HQC). Among these, the AIC was prioritized because it is widely regarded as more reliable in small-to medium-sized samples and has been frequently adopted in empirical ARDL applications. By selecting the lag structure that minimizes the AIC, the model ensures efficiency in short-run dynamics and consistency in long-run estimates.

Another strength of the ARDL framework lies in its bounds testing approach, which is often considered superior to conventional cointegration methods. Furthermore, the ARDL model facilitates the derivation of an Error Correction Model (ECM), enabling the joint estimation of short- and long-run dynamics. The inclusion of sufficient lag structures also helps to mitigate serial correlation and endogeneity concerns, enhancing the reliability of the results (Hussain et al., 2023; Shahid et al., 2024). Equation (3) specifies the ARDL model employed to estimate the coefficients of the long-run relationships among the variables.

$$\begin{aligned} \Delta LE_t = & \beta_0 + \beta_1 LE_{t-1} + \beta_2 LY_{t-1} + \beta_3 LT_{t-1} + \beta_4 LR_{t-1} + \beta_5 LW_{t-1} \\ & + \sum_{i=1}^q \alpha_1 \Delta LE_{t-i} + \sum_{i=1}^q \alpha_2 \Delta LY_{t-i} + \sum_{i=1}^q \alpha_3 \Delta LT_{t-i} + \sum_{i=1}^q \alpha_4 \Delta LR_{t-i} \\ & + \sum_{i=1}^q \alpha_5 \Delta LW_{t-i} + \varepsilon_t \end{aligned} \quad (3)$$

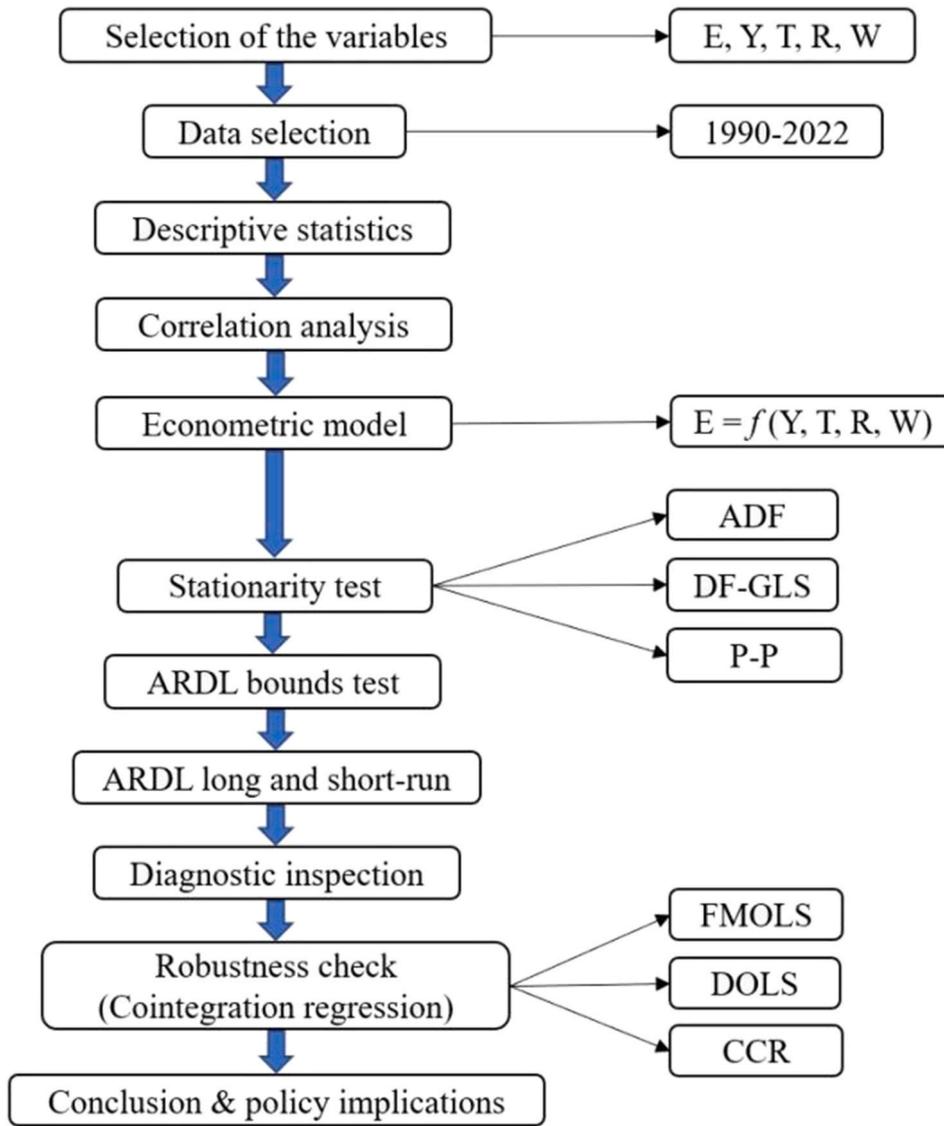


Fig. 1. Flowchart of the analysis.

where q denotes the lag length of the series, and Δ represents the first-difference operator.

First, the study estimates the long-run effects of the variables, followed by the short-run dynamics, including the ECM. The ECM measures the speed at which the model adjusts from a previous equilibrium toward the current period. A significantly negative ECM coefficient indicates the presence of cointegration among the variables. The ECM representation of the ARDL model is specified as follows:

$$\begin{aligned} \Delta LE_t = & \beta_0 + \beta_1 LE_{t-1} + \beta_2 LY_{t-1} + \beta_3 LT_{t-1} + \beta_4 LR_{t-1} + \beta_5 LW_{t-1} \\ & + \sum_{i=1}^q \alpha_1 \Delta LE_{t-i} + \sum_{i=1}^q \alpha_2 \Delta LY_{t-i} + \sum_{i=1}^q \alpha_3 \Delta LT_{t-i} + \sum_{i=1}^q \alpha_4 \Delta LR_{t-i} \\ & + \sum_{i=1}^q \alpha_5 \Delta LW_{t-i} + \theta ECM_{t-1} + \varepsilon_t \end{aligned} \quad (4)$$

where θ denotes the coefficient of the ECM.

4.5. Robustness check with FMOLS, DOLS, and CCR

To ensure robustness and validate the assumptions of the ARDL model, this study also employed alternative cointegration techniques,

namely the FMOLS method (Phillips & Hansen, 1990), the DOLS method (Stock & Watson, 1993), and the CCR method (Park, 1992). These approaches strengthen the reliability of the estimated parameters and mitigate concerns regarding the validity of the cointegration results. Prior studies have confirmed the suitability of FMOLS, DOLS, and CCR as complementary tools for verifying ARDL outcomes (Idroes et al., 2024; Pattak et al., 2023). Each method offers distinct advantages.

The FMOLS procedure is semi-parametric and widely applied in the estimation of long-run coefficients. It effectively addresses issues of endogeneity, omitted variable bias, serial correlation, and functional form errors, even in small samples. FMOLS is particularly useful for approximating the existence of a single cointegrating relationship among variables integrated of order one, $I(1)$. Additionally, it overcomes several limitations of traditional cointegration methods and provides reliable long-run estimates (Degbedji et al., 2024; Phillips & Hansen, 1990).

By contrast, the DOLS approach employs a parametric strategy for estimating long-run relationships in models with regressors of varying integration orders. It demonstrates desirable properties of unbiasedness and asymptotic efficiency, even in the presence of endogeneity. Stock and Watson (1993) further argued that the inclusion of leads and lags of differenced regressors helps correct for autocorrelation and

non-normality in the residuals.

Finally, the CCR methodology evaluates cointegrating vectors in I(1) models. While closely related to FMOLS, it differs in its focus: CCR primarily applies transformations to the data itself, whereas FMOLS transforms both data and parameters (Park, 1992). This distinction highlights the complementary value of CCR in validating cointegration estimates.

5. Empirical results and analysis

At the preliminary stage, this study examined the selected variables prior to model estimation. Alongside correlation analysis, Table 2 presents the results of the descriptive statistics. The mean and median values of all variables indicate that the dataset is approximately normally distributed. Skewness values close to zero further suggest near-normality; specifically, GHG emissions and GDP display negative skewness, while the remaining variables show positive skewness. The kurtosis values, all below 3, indicate that the series exhibits platykurtic characteristics. Moreover, the low Jarque–Bera probabilities confirm that the variables follow a normal distribution. The correlation analysis, reported in Table 3, shows that LE, LY, LT, and LR are positively correlated with one another, whereas LW exhibits a negative association with the other variables.

The results of ADF, DF-GLS, and P-P unit root tests (Table 4) indicated that the variables—economic growth, technological innovation, renewable energy, women’s empowerment, and GHG emissions—were non-stationary at their levels, I(0), but became stationary after first differencing, I(1). This finding implies that the series are integrated of order one, I(1). The presence of I(1) variables confirms the suitability of the ARDL bounds testing approach, which allows for the inclusion of variables with mixed integration orders (I(0) and I(1)) but is invalid if any series is integrated of order two, I(2). Thus, the unit root testing results establish a sound statistical basis for proceeding with the ARDL modeling framework.

The ARDL bounds test, which assesses the existence of cointegration among the variables, is reported in Table 5. The results indicate that for both order zero and order one, the estimated F-statistic (15.41) exceeds the upper critical bounds at the 10 %, 5 %, 2.5 %, and 1 % significance levels. This confirms the presence of a stable long-run relationship among the variables, leading to the rejection of the null hypothesis of no cointegration.

The short- and long-run results derived from the ARDL framework are reported in Table 6. The estimates indicate a significant positive relationship between GDP growth and GHG emissions in both time horizons. Specifically, a 1 % increase in economic growth raises GHG emissions by 0.13 % in the short run and 0.30 % in the long run, thereby exacerbating environmental degradation. This outcome can be attributed to intensified economic activities heavily dependent on fossil fuels. These findings support the acceptance of the null hypothesis, suggesting that economic growth does not alleviate environmental pressures at the global level.

In contrast, technological advancement plays a crucial role in improving ecological quality, as reflected in its negative and statistically

Table 2
Descriptive statistics.

Variables	LE	LY	LT	LR	LW
Mean	17.4806	8.9265	14.3896	2.8634	3.5343
Median	17.5076	8.9640	14.3987	2.8492	3.5486
Maximum	17.7377	9.4484	15.0396	3.0573	3.7941
Minimum	17.2375	8.3740	13.6970	2.8052	3.2701
Skewness	-0.0861	-0.0906	0.0394	0.0969	0.0307
Kurtosis	1.4763	1.4109	1.6903	2.6558	1.8887
Jarque-Bera	3.2331	3.5172	2.4034	3.8740	1.7032
Probability	0.1986	0.1723	0.3007	0.1715	0.4267
Observations	33	33	33	33	33

Table 3
Correlation analysis.

	LE	LY	LT	LR	LW
LE	1.0000				
LY	0.9923	1.0000			
LT	0.9828	0.9634	1.0000		
LR	0.4440	0.4314	0.5186	1.0000	
LW	-0.9741	-0.9607	-0.9897	-0.5541	1.0000

significant association with GHG emissions. A 1 % increase in technological progress reduces global emissions by 0.003 % in the short run and 0.08 % in the long run. This reduction may be attributed to the adoption of cleaner technologies, improved energy efficiency, and innovations aimed at pollution abatement. Accordingly, the null hypothesis is rejected in favor of the alternative, confirming that technological innovation mitigates ecological challenges worldwide by lowering GHG emissions.

The ARDL estimation further reveals a negative relationship between global GHG emissions and renewable energy consumption, indicating that the use of sustainable energy improves ecological quality worldwide. Specifically, renewable energy consumption reduces GHG emissions by 0.17 % in the short run and 0.19 % in the long run. This outcome can be attributed to the increasing deployment of renewable energy across residential, industrial, manufacturing, and commercial sectors. Accordingly, the null hypothesis is rejected in favor of the alternative, underscoring that greater reliance on green energy plays a central role in mitigating biodiversity loss and curbing global emissions.

Similarly, the ARDL results highlight the positive role of women’s empowerment in reducing environmental degradation. A 1 % increase in female empowerment reduces global GHG emissions by 0.14 % in the medium run and 0.09 % in the long run. These findings suggest that enhanced female participation—particularly in leadership positions and within the green energy sector—raises environmental awareness and supports policies aimed at reducing emissions, thereby promoting long-term sustainability. Thus, the null hypothesis is rejected, and the alternative is accepted, affirming that women’s empowerment significantly contributes to alleviating ecological challenges worldwide.

The model’s error correction mechanism (ECM) also provides robust evidence. The coefficient of the ECM is negative and highly significant at the 1 % level, indicating strong adjustment dynamics. The results suggest that approximately 63 % of disequilibrium is corrected annually, reflecting a rapid convergence toward long-run equilibrium. The long-run estimation further reports an R² of 0.9957 and an adjusted R² of 0.9950, showing that the explanatory variables account for nearly all the variation in environmental quality.

Finally, several diagnostic tests (Table 7) confirm the validity of the ARDL model. The Jarque–Bera statistic and corresponding p-values indicate that the residuals are normally distributed. The Breusch–Godfrey LM test suggests no evidence of serial correlation, while the Breusch–Pagan–Godfrey test indicates the absence of heteroscedasticity. The Ramsey RESET test confirms that the model is properly specified. In addition, the Hausman (1978) test for endogeneity reveals no statistically significant evidence of endogeneity, supporting the null hypothesis of “no endogeneity.” Together, these diagnostics confirm that the model is well-specified, stable, and yields consistent coefficient estimates.

In addition, this study applied the CUSUM and CUSUMSQ tests on the residuals to verify model stability. Fig. 2 presents the CUSUM and CUSUMSQ plots at the 5 % significance level, where the red lines represent the confidence bounds and the blue line traces the residuals. Since the residuals remain within the confidence limits, the results confirm that the model is stable. Overall, the diagnostic tests demonstrate that the ARDL model is appropriately specified and provides a good fit.

As a robustness check, this study employed FMOLS, DOLS, and CCR

Table 4
Results of unit root tests.

Variables		LE	LY	LT	LR	LW
ADF	I(0)	-0.1449	-0.5673	0.0262	0.4491	-1.1256
	I(1)	-5.981***	-4.6716***	-6.4809***	-5.2471***	-5.0604***
DF-GLS	I(0)	0.9504	0.6507	-0.2822	-0.0209	-0.3063
	I(1)	-5.8835***	-4.7368***	-5.7388***	-4.5918***	-4.1262***
P-P	I(0)	-0.1169	-0.5844	-0.0284	0.4088	-1.3590
	I(1)	-5.9891***	-4.6840***	-6.4809***	-5.4672***	-6.4006***

Note: ***p < 0.01.

Table 5
Results of the ARDL bounds test.

Test statistic	Value	Significance levels	I(0)	I(1)
F-statistic	15.4114	10 %	2.20	3.09
K	4	5 %	2.56	3.49
		2.5 %	2.88	3.87
		1 %	3.29	4.37

estimations (Table 8). The results from all three methods consistently show that economic growth is positively associated with GHG emissions, indicating that environmental quality deteriorates as economies expand. In contrast, technological advancement, renewable energy adoption, and women’s empowerment contribute to long-term reductions in emissions, thereby mitigating environmental degradation. Across the three models, the high R² and adjusted R² values—explaining nearly 99 % of the variation in the dependent variable—confirm the strong explanatory power and reliability of the estimates.

The integrated economy–technology–energy–empowerment nexus derived from the empirical findings is portrayed in Fig. 3. The analysis demonstrates that economic growth increases GHG emissions, underscoring its negative environmental impact, while technological innovation, renewable energy adoption, and women’s empowerment exert positive effects by reducing emissions and strengthening ecological resilience. The synergies among these positive drivers reveal that women’s empowerment facilitates the diffusion of clean technologies and supports renewable energy adoption, thereby reinforcing global sustainability pathways. Overall, the figure illustrates that achieving environmental sustainability requires not only decoupling economic growth from emissions but also harnessing social inclusion, technological advancement, and green energy transitions as mutually reinforcing strategies.

6. Discussion

6.1. Economic growth and environmental sustainability

The present research examines the global relationship between GDP growth, technological advancement, renewable energy, gender equality, and environmental sustainability. The findings reveal a significant

positive association between GDP expansion and GHG emissions in both the short and long run. This outcome aligns with earlier studies (Behera et al., 2024a; Chien et al., 2022; Das & Sethi, 2023; Hassan et al., 2024; Kim, 2020; Raihan, 2023b; Sahoo et al., 2023; Tariq et al., 2022; Usman et al., 2023; Wahab et al., 2024), which consistently document the link between economic growth and environmental degradation. Previous research highlights that when growth is pursued without adequate environmental considerations—particularly in least-developed economies—it accelerates ecological damage. These economies often depend heavily on agriculture and industry, sectors that consume large amounts of fossil fuel energy and generate high levels of pollution. Limited access to modern technologies, coupled with demographic pressures, low incomes, and restricted employment opportunities, exacerbates their reliance on outdated and inefficient energy sources. While economic expansion improves living standards by raising incomes and creating jobs, it simultaneously undermines environmental quality through extensive use of conventional fuels.

Nevertheless, a strand of the literature (Acheampong & Opoku, 2023; Dissanayake et al., 2023; Namahoro et al., 2021; Onofrei et al.,

Table 7
Results of ARDL model diagnostic tests.

Diagnostic tests	Coefficient	p-value	Decision
Jarque-Bera test	0.2439	0.8852	Normally distributed residuals
Breusch-Godfrey LM test	1.8658	0.1749	No serial correlation
Breusch-Pagan-Godfrey test	1.7748	0.1620	No heteroscedasticity
Ramsey RESET test	0.9582	0.3465	Properly specified model
Hausman specification test	2.4083	0.6824	No endogeneity

Table 6
ARDL long and short-run results.

Variables	Long-run			Short-run		
	Coefficient	t-statistic	p-value	Coefficient	t-statistic	p-value
LY	0.2964***	11.9972	0.0000	0.1289***	9.5457	0.0000
LT	-0.0793***	-3.6006	0.0098	-0.0032**	-2.4233	0.0169
LR	-0.1906***	-5.4017	0.0000	-0.1687***	-8.2521	0.0000
LW	-0.1407***	-4.0128	0.0031	-0.0923***	-3.1929	0.0044
C	11.9322	1.2687	0.1207	-	-	-
ECM (-1)	-	-	-	-0.6329***	-4.9349	0.0000
R ²	0.9957					
Adjusted R ²	0.9950					

Note: ***p < 0.01, **p < 0.05.

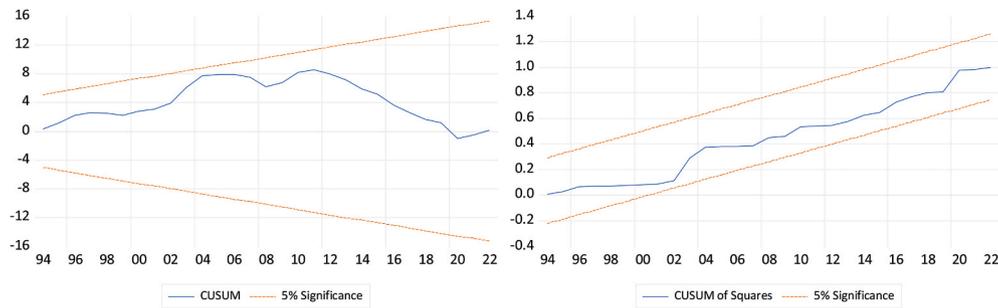


Fig. 2. The results of the CUSUM and CUSUMSQ tests.

Table 8
Results of the robustness check.

Variables	FMOLS		DOLS		CCR	
	Coefficient	t-statistic	Coefficient	t-statistic	Coefficient	t-statistic
LY	0.2909***	12.6003	0.2706***	5.2196	0.2969***	11.4051
LT	-0.0772***	-3.6535	-0.0789***	-3.2085	-0.0783***	-3.0755
LR	-0.2062***	-5.3066	-0.1824***	-3.5536	-0.1991***	-5.9382
LW	-0.1402***	-4.1865	-0.1481***	-3.3251	-0.1339***	-4.0929
C	11.6425	1.1456	17.4822	1.2137	11.6571	1.0621
R ²	0.9953		0.9996		0.9952	
Adjusted R ²	0.9946		0.9991		0.9945	

Note: ***p < 0.01.

2022; Raihan & Tuspekova, 2022b) presents contrasting evidence, suggesting that economic development can reduce emissions when accompanied by technological progress. These studies argue that the integration of modern technologies into industrial processes enables countries to sustain or even increase output while lowering energy use and CO₂ emissions. The positive correlation between economic growth and GHG emissions found in this study can be explained by several factors. Governments in the early stages of development often prioritize GDP growth over sustainability, leading to the adoption of low-quality machinery and outdated production methods. The continued reliance on fossil fuels and other non-renewable resources further accelerates environmental degradation. Thus, developing countries must urgently transition to advanced, cleaner energy systems, particularly in high-emission sectors such as agriculture and large-scale manufacturing, to achieve growth without escalating environmental harm.

The evidence also underscores the strong link between income

growth and GHG emissions, reinforced by the structural shift of many emerging economies toward energy-intensive industrialization. To break this cycle, countries must move away from the “pollute first, then treat later” approach, instead embedding sustainability as a prerequisite for economic expansion. Comprehensive environmental regulations covering key industries—including shipbuilding, chemicals, and leather processing—are essential to balance economic growth with ecological protection. As industries in emerging economies remain heavily dependent on fossil fuels, unchecked industrial expansion contributes directly to higher emissions. Infrastructure development, trade promotion, and capital utilization drive investment and industrial productivity, but without effective environmental governance, exacerbate ecological pressures.

The finding that economic growth significantly increases GHG emissions reinforces the urgent need to decouple economic expansion from environmental degradation. Growth-oriented policies reliant on

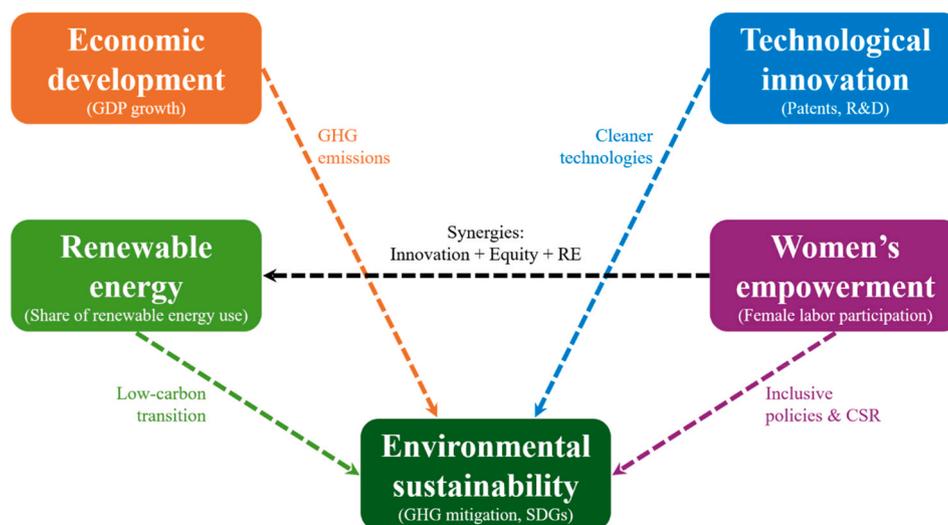


Fig. 3. The integrated economy–technology–energy–empowerment nexus and its implications for environmental sustainability.

fossil fuels and resource-intensive industries accelerate ecological decline. Therefore, future development strategies must prioritize low-carbon technologies, circular economy practices, and stricter regulatory frameworks to ensure that rising income and productivity are achieved without compromising ecological integrity.

6.2. Technological innovation and environmental sustainability

From a global perspective, this study finds promising evidence on the role of technological innovation in mitigating environmental degradation. The results indicate that higher patent applications are associated with lower GHG emissions, suggesting that integrating sustainable innovations into production processes can significantly improve biodiversity outcomes by reducing pollution. These findings are consistent with prior research (Alola & Adebayo, 2023; Behera et al., 2024b; Raihan, 2023b; Sahoo et al., 2023; Usman et al., 2023; Hassan et al., 2024), which highlights the positive contribution of technological progress to ecosystem health. Previous studies have shown that advanced technologies reduce emissions by lowering energy consumption per unit of output and by embedding clean energy systems in modern equipment (Behera et al., 2024c). For instance, several countries have successfully replaced conventional energy in agriculture and large-scale manufacturing with eco-friendly alternatives, thereby reducing pollution.

Nonetheless, some scholars have challenged these optimistic views. Su et al. (2021) and Sethi, Behera, and Sethi (2024) contend that certain technological innovations—particularly those reliant on fossil fuel engines such as diesel and petrol—have aggravated environmental degradation. While such technologies may boost productivity, global trade, and cost efficiency, they also emit harmful pollutants that undermine ecological quality. Despite these drawbacks, the overall evidence supports a net positive effect of technological innovation on environmental sustainability. This reinforces the imperative of directing innovations toward high-emission sectors, where improvements in production processes can yield significant reductions in GHG emissions.

It is also important to acknowledge that technological innovation alone has a more limited impact on emission reduction compared with renewable energy adoption and women's empowerment. In some countries, insufficient emphasis on low-carbon innovation constrains progress toward sustainability. Expanding investments in environmentally friendly technologies—particularly through patent activity—can play a critical role in addressing climate change while supporting long-term development.

The findings confirm that technological innovation is vital to reducing emissions, underscoring the importance of prioritizing green R&D, patent generation, and the diffusion of eco-friendly technologies in climate policy. Governments and international organizations should incentivize clean innovations through subsidies, intellectual property protections, and cross-border technology transfers. Moreover, policies that encourage commercialization and large-scale adoption of environmentally sound technologies will accelerate the transition to sustainable production and consumption systems.

6.3. Green energy and environmental sustainability

This research investigates the global potential of renewable energy adoption for advancing environmental sustainability. The empirical results highlight the necessity of expanding the share of green energy in the overall energy mix, as doing so significantly reduces GHG emissions. Renewable energy sources—such as wind, geothermal, solar, and hydropower—emit little to no greenhouse gases, thereby supporting ecological sustainability. Accordingly, countries dependent on fossil fuels should urgently prioritize a transition toward clean energy, facilitated by major investments in environmentally friendly technologies and infrastructure. These findings are consistent with prior research (Behera et al., 2024d; Chien et al., 2022; Hassan et al., 2024; Kim, 2020;

Sahoo et al., 2023; Sethi, Behera, & Sethi, 2024; Tariq et al., 2022; Usman et al., 2023; Wahab et al., 2024), all of which emphasize the beneficial environmental impacts of renewable energy adoption. Beyond mitigating GHG emissions, clean energy also delivers economic and strategic benefits, including greater energy accessibility, improved energy security, and reduced dependence on imported fuels.

Developing economies face particular challenges, as their energy systems remain heavily reliant on imported crude oil, natural gas, coal, and petroleum products. The depletion of these finite resources threatens long-term energy security, especially amid rising consumption driven by rapid economic growth. Renewable energy—particularly solar, wind, hydro, and biomass—offers a viable solution to these challenges. However, social, political, economic, technological, and institutional barriers often impede the sustainable adoption of these resources (Sethi, Behera, Behera, & Sethi, 2024). Effective integration of renewable energy into the power sector requires supportive policy frameworks that strengthen financial, legal, and technological infrastructure. Establishing specialized green energy agencies within government institutions could accelerate the scaling of sustainable energy systems.

The strong and consistent evidence for the environmental benefits of renewable energy underscores the urgency of transitioning away from fossil fuels. Policymakers must prioritize investment in renewable infrastructure, cost reduction for clean technologies, and improvements in grid integration. Because renewable energy simultaneously reduces ecological vulnerabilities and enhances energy security, it should be viewed not only as an environmental imperative but also as an economic and geopolitical necessity.

A comprehensive strategy is needed to support the transition to a low-carbon society. In sun-rich countries, for example, solar energy offers vast untapped potential. Governments should harness this resource through targeted policies and infrastructure development, such as promoting solar household systems in rural and coastal areas where kerosene remains prevalent, or encouraging rooftop solar in metropolitan regions. Additional measures include replacing diesel-powered irrigation pumps with solar-powered systems and expanding the use of mini-grids in remote areas where grid extension is costly. Establishing infrastructure development institutions to promote, finance, and manage renewable projects could accelerate this transition. Such initiatives would reduce dependence on fossil fuels, cut GHG emissions, and strengthen long-term sustainability.

6.4. Women's empowerment and environmental sustainability

This study delivers substantial findings on the connection between women's empowerment and global environmental sustainability. The empirical evidence demonstrates that greater female empowerment is associated with significant reductions in GHG emissions, underscoring its positive impact on ecological quality in both the short and long term. These effects can be linked to the growing presence of women in leadership positions—such as board members and CEOs—who often advocate for environmentally sustainable legislation and eco-conscious business practices. More broadly, women's empowerment enhances participation in politics, access to education, employment creation, and awareness of sustainable living, particularly in rural areas where the shift toward modern energy services has a pronounced effect on reducing emissions. Previous studies (Achuo et al., 2022; Jiang & Akbar, 2018; Li et al., 2024; Lv & Deng, 2019; Mujeed et al., 2021; Wei et al., 2021) support these findings, showing that women's involvement in agriculture and industry contributes to mitigating environmental degradation. By fostering financial independence and greater access to advanced energy technologies, empowered women are more likely to support investments in energy efficiency and renewable energy, thereby improving environmental quality at a broader scale.

This research also examines the intersection of gender, innovation, and climate change, with a particular focus on women in science and

research. Xie et al. (2020) highlight the distinct strengths of female R&D personnel, who demonstrate exceptional efficiency in scientific research, compared with male researchers who excel in technological development. In the current context—where climate change policies demand inclusive decision-making—the findings emphasize the importance of expanding women's participation in global warming strategies, particularly in research and patent development. Policies and funding mechanisms that support women's engagement in R&D could significantly increase the creation of patents directly targeting climate change mitigation. The study underscores the need for closer evaluation of women's contributions to publicly funded research and patent activity, with important implications for climate innovation policy.

Overall, women's empowerment emerges as a central, yet often overlooked, determinant of environmental outcomes. By showing that female labor force participation reduces emissions, the study highlights the critical importance of integrating gender equality into environmental and energy policy. Women influence household energy choices, drive green entrepreneurship, and strengthen governance through inclusive decision-making. Expanding women's access to education, leadership, and financial resources can therefore simultaneously advance gender equity and environmental sustainability.

Finally, the interplay among technological innovation, renewable energy adoption, and women's empowerment demonstrates that sustainability cannot be achieved through isolated interventions. Instead, it requires integrated strategies that align economic development with social inclusion and technological progress. International cooperation, capacity building, and cross-sectoral partnerships are essential to ensure that green innovations and transitions are accessible worldwide, particularly in developing economies facing the greatest vulnerabilities. Collectively, these results call for policies that are not only environmentally effective but also socially inclusive, laying the foundation for a more sustainable and equitable global future.

7. Conclusions and implications

7.1. Conclusions

This study investigates the impact of technological innovation, renewable energy, GDP growth, and women's empowerment on global environmental sustainability, using time-series data from 189 countries over the period 1990–2022. The stationarity of the data series was confirmed using ADF, DF-GLS, and P–P unit root tests, while the ARDL bounds test indicated a long-run cointegrating relationship among the variables. The ARDL results reveal that global GHG emissions rise in parallel with economic growth, whereas renewable energy adoption, technological progress, and women's empowerment contribute to improved environmental quality. These findings were further validated through robustness checks using FMOLS, CCR, and DOLS estimators.

By integrating social, economic, and technological dimensions, this study expands the existing literature and provides a comprehensive understanding of the nexus between women's empowerment, economic growth, technological innovation, renewable energy, and environmental sustainability. The results highlight the critical role of promoting renewable energy, advancing green technologies, and strengthening women's empowerment as effective strategies to curb emissions and foster sustainability. Furthermore, the study underscores the importance of strong regulatory frameworks to ensure that global climate objectives are met. Collectively, the findings suggest that aligning economic expansion with gender equality and clean energy transitions is central to achieving a sustainable future.

7.2. Implications

7.2.1. Theoretical implications

The theoretical implication of achieving environmental sustainability through economic growth is that a well-regulated economy can

transition toward eco-friendly practices by investing in green technologies, improving resource efficiency, and internalizing environmental costs within market mechanisms. Such an approach enables continued economic development while limiting ecological harm, thereby fostering sustainability for future generations. This, however, requires carefully designed policies that reconcile growth with environmental protection, recognizing that the specific trajectory will vary depending on each nation's economic context.

Theoretical implications of sustainability through green energy include reduced environmental impacts, sustainable long-term growth, enhanced energy security, rural and regional development, domestic industry advancement, job creation, and significant reductions in GHG emissions. Energy transition—shifting from fossil fuel dependency to renewable and eco-friendly alternatives—is therefore essential. This transition is driven by environmental imperatives, economic incentives, and technological progress.

From a technological perspective, the theoretical implications suggest that innovation can substantially reduce environmental degradation by optimizing resource use, minimizing waste, advancing cleaner energy adoption, and improving monitoring and management practices. At the same time, critical considerations arise regarding unintended consequences, equitable access to these innovations, and the need for robust policy frameworks to govern their development and diffusion.

Finally, the theoretical implication of linking women's empowerment to sustainability is that enhancing women's agency and decision-making power, particularly in communities most affected by environmental challenges, promotes more sustainable practices. These include improved resource management, greater involvement in conservation efforts, and stronger climate adaptation strategies. Women's distinct perspectives and deep connections to local ecosystems can therefore contribute meaningfully to fostering sustainability at both local and global levels.

7.2.2. Policy implications

The findings of this study offer clear guidance for policymakers seeking to balance economic growth with environmental sustainability. The evidence that economic growth continues to drive GHG emissions highlights the need for governments to adopt development strategies that decouple income expansion from fossil fuel consumption. In emerging economies, where industrialization remains heavily reliant on coal and oil, policies should prioritize investments in low-carbon technologies, stricter environmental standards for industries, and the gradual phase-out of subsidies for fossil fuels. For advanced economies, the focus should shift toward accelerating carbon-neutral growth by expanding green infrastructure, strengthening carbon pricing mechanisms, and fostering circular economy practices that reduce resource waste.

Technological innovation plays a central role in mitigating environmental degradation, suggesting that public and private investment in R&D must be scaled up globally. In industrialized countries, policies should support the diffusion of cutting-edge clean technologies into developing economies through financial support, technology transfer, and capacity-building initiatives. In lower-income regions, governments should strengthen domestic innovation ecosystems by creating innovation hubs, offering tax incentives for green start-ups, and integrating sustainability principles into national education systems to cultivate human capital capable of driving environmentally conscious technological progress.

The strong positive impact of renewable energy on reducing emissions calls for a renewed emphasis on energy transitions tailored to regional contexts. In Sub-Saharan Africa, where energy access remains a major challenge, decentralized solar and wind systems should be prioritized to expand access while avoiding carbon-intensive pathways. In South Asia and Southeast Asia, where coal still dominates the energy mix, policies should encourage large-scale renewable energy projects supported by international climate finance. In advanced economies, the

focus should be on achieving full grid integration of renewables, investing in storage technologies, and modernizing energy infrastructure to ensure reliability in high-renewable systems.

The study also highlights women's empowerment as a critical yet underutilized lever for sustainability. Policies should aim to mainstream gender considerations into climate and energy frameworks by enhancing women's access to green jobs, leadership positions, and entrepreneurship opportunities in renewable energy and technology sectors. In rural areas of developing countries, targeted programs that empower women to adopt and disseminate clean cooking technologies and renewable household energy systems can reduce emissions while improving health outcomes. In more advanced economies, ensuring gender parity in corporate and political leadership can help strengthen climate governance and align sustainability goals with social equity.

Finally, the interplay between technological innovation, renewable energy adoption, and women's empowerment suggests that integrated policies will yield the greatest benefits. Governments should not pursue these levers in isolation but design multi-sectoral strategies that connect innovation policy with energy transitions and gender equality frameworks. For instance, international development agencies could create financing instruments that support renewable energy projects led by women entrepreneurs, thereby reinforcing the dual goals of sustainability and inclusion. Such targeted, regionally sensitive interventions can transform the structural drivers of emissions, offering a pathway to a resilient and low-carbon global future.

7.3. Limitations and future research

There are several avenues through which future iterations of this study could be refined in terms of scope and methodological depth. First, the reliance on time-series data in the present analysis limits its generalizability. Future research could adopt panel data techniques to encompass a broader set of countries, including OECD, BRI, MENA, and BRICS regions, thereby providing more comprehensive insights. Second, this study covers a 33-year period (1990–2022), constrained by the limited availability of data on technological innovation and women's empowerment. With expanded datasets, future studies could extend the temporal horizon to four or five decades, enhancing the robustness of long-term inferences.

Third, while the current study focuses on four primary determinants of environmental quality—economic growth, technological innovation, renewable energy, and women's empowerment—future research could integrate additional variables such as poverty alleviation, income inequality, and financial development, which may also play a significant role in shaping environmental outcomes. Finally, methodological advancements could be leveraged by applying more sophisticated approaches for time-series analysis, including Wavelet Analysis, Deep Learning models, Dynamic Bayesian Networks, and Structural Time-Series Models. Incorporating these advanced techniques would provide deeper insights into the dynamic and nonlinear relationships underpinning global environmental sustainability.

CRedit authorship contribution statement

Asif Raihan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Mohammad Ridwan:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Syed Masiur Rahman:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Investigation. **Tapan Sarker:** Writing – review & editing, Validation, Supervision, Investigation. **Filiz Guneyso Atasoy:** Writing – review & editing, Validation, Investigation. **Samanta Islam:** Writing – review & editing, Investigation. **Mifthaul Arefine Kakon:** Writing – review & editing. **Runa Akter:** Writing – review & editing, Investigation.

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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