

Research

The effects of natural resources, education, and financial inclusion in achieving environmental sustainability in resources-abundance nations

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Abstract

This study investigates the interplay between income from natural resources, education, access to financial services, and technological advancements in achieving Sustainable Development Goals (SDGs) 7 and 13 in eight resource-rich countries. Motivated by the global urgency for sustainable practices, this research employs a robust analytical framework to explore short- and long-term interactions among these variables, including panel data analysis, cointegration tests, and asymmetry coefficient estimation. Key findings reveal that income from natural resources is directly linked to increased CO2 emissions, emphasizing the environmental costs of resource exploitation. Conversely, higher education levels are associated with reduced CO2 emissions and ecological footprints, highlighting education’s vital role in environmental sustainability. At the same time, financial inclusion fosters economic growth and contributes to environmental degradation, necessitating regulatory measures. Technological innovation, particularly green technology, is crucial for mitigating environmental impacts. This study uniquely combines these factors to provide empirical evidence of their collective influence on sustainability, filling a gap in existing research. The results suggest that effective governance, environmental education, alignment of financial practices with sustainability goals, and support for green innovation are essential for harmonizing economic development with environmental conservation.

Graphical Abstract



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Keywords Sustainable development goals (SDGs) · Natural resources · Education · Financial inclusion · Environmental sustainability · CO2 emissions

1 Introduction

The Sustainable Development Goals (SDGs) substantially influence impoverished nations, offering a transformative framework for fostering social, economic, and environmental advancement. The objectives above encompass a wide range of pressing issues, such as the elimination of poverty, the provision of quality education, the promotion of gender equality, the facilitation of access to clean water and sanitation, the advancement of affordable and sustainable energy sources, the promotion of economic development, and the establishment of sustainable cities and communities [1–3]. In pursuing Sustainable Development Goal 7, which aims to achieve universal access to affordable, reliable, and modern energy services, significant progress is also made towards attaining Sustainable Development Goal 4 [4]. This goal strives to ensure inclusive and high-quality education for all individuals. In addition, adopting sustainable energy practices cultivates a mindset focused on reducing carbon emissions among future generations. Thus, in turn, contributes to the imperative actions outlined in SDG 13, which aim to address climate change and its wide-ranging consequences. The transformation of the educational landscape necessitates collaborative endeavors [5]. Governments, international organizations, private entities, and civil society must engage in collaborative efforts to formulate policies, secure adequate funding, and effectively implement sustainable energy solutions within educational facilities on a global scale [6].

The present study has considered natural resources, financial inclusion, education, and innovation in the sustainable economic and energy aspects equation linked to SDGs 7 and 13. Financial inclusion has the potential to make a substantial contribution to the comprehensive economic development of a given region. This, in turn, can facilitate promoting and advancing eco-innovation and sustainable development [7]. However, it is essential to acknowledge that the notion of financial inclusion may possess certain limitations in its ability to foster sustainable development within the framework of economic globalization and climate change [8]. Financial inclusion has the potential to effectively facilitate the accessibility of financial services for rural households, thereby significantly enhancing their economic resilience and fostering sustainable development. Therefore, assessing the importance of financial development and inclusion in enhancing environmental and energy sustainability is crucial. Technological innovation possesses significant potential to drive the progression of environmental sustainability. One illustrative example pertains to the potential of green innovation in mitigating the adverse consequences of extracting natural resources from the environment [9]. Technological innovation possesses the inherent capacity to effectively facilitate the widespread adoption of renewable energy sources, thus assuming a pivotal role in advancing environmental and energy sustainability. This objective is accomplished by mitigating carbon dioxide (CO₂) emissions and promoting the development of sustainable energy practices [10, 11]. Education plays a crucial role in promoting and advancing environmental sustainability by facilitating the dissemination of knowledge and advocating for adopting sustainable practices. Education plays a pivotal role in cultivating a comprehensive comprehension among individuals and businesses concerning the importance of natural resources and the necessity to protect them [12]. Therefore, it is crucial to advocate for educational initiatives and awareness campaigns to promote sustainable practices and protect the environment [13]. Natural resources possess the inherent capacity to contribute to economic development substantially. Nevertheless, it is of utmost importance to recognize and acknowledge that utilizing these resources can also lead to detrimental consequences in terms of environmental degradation [14]. Therefore, it is essential to comprehensively examine the relationship between natural resources and economic development, along with the potential impact of green innovation and financial inclusion in promoting sustainable growth [15]. Natural resources can also play a significant role in promoting the adoption of renewable energy consumption, thereby making a valuable contribution to environment.

The primary objective of this study was to investigate the complex interplay between natural resource rent, education, financial inclusion, and technological innovation in achieving Sustainable Development Goals (SDGs) 7 and 13 in eight resource-rich countries. Specifically, the research aimed to:

1. Examine how income from natural resources impacts CO₂ emissions and energy sustainability.
2. Assess the role of education in reducing CO₂ emissions and promoting clean energy awareness.
3. Analyze the effects of financial inclusion on both clean energy inclusion and environmental degradation.

4. Evaluate the contribution of technological innovation, mainly green technologies, in mitigating environmental impacts and accelerating clean energy sources.

Environmental sustainability remains a pressing challenge for resource-rich nations as they grapple with balancing economic growth and ecological preservation. This study provides an innovative perspective on this challenge by examining the interplay of natural resource rents, education, financial inclusion, and technological innovation within Sustainable Development Goals (SDGs) 7 and 13. While prior research has extensively explored these factors in isolation, this study uniquely integrates them to analyze their collective influence on sustainability outcomes. Specifically, it identifies the dynamics between these variables and their dual implications for environmental degradation and sustainable energy practices.

The objectives of this research are twofold. First, it seeks to delineate the complex interactions between natural resource income and CO₂ emissions, thereby unraveling the environmental consequences of resource dependency. Second, it aims to highlight the role of education in fostering environmental consciousness and reducing ecological footprints. Additionally, the study evaluates financial inclusion's dual nature—its capacity to enhance economic resilience and its potential to exacerbate environmental degradation. Lastly, the research assesses the pivotal role of technological innovation in promoting green technologies to mitigate environmental impacts. By employing advanced econometric techniques, including panel data analysis, cointegration tests, and asymmetric modeling, this study addresses gaps in empirical evidence and provides nuanced insights for policymakers. Its findings have significant implications for designing integrated strategies to harmonize economic growth with ecological stewardship in resource-abundant nations.

This research contributes to the existing literature in several ways. First, it bridges the gap between natural resource management and sustainability studies by quantifying the environmental trade-offs associated with resource exploitation. While existing studies predominantly focus on individual variables, this research adopts a holistic approach, examining the interdependencies among multiple socio-economic factors. Second, the inclusion of financial inclusion and technological innovation offers a novel lens to understand their complementary roles in advancing SDGs 7 and 13. Although celebrated for driving economic growth, financial inclusion is critically analyzed here for its unintended environmental consequences. Similarly, the study provides robust empirical evidence on how green innovations can offset the ecological costs of resource rents. Third, it underscores the transformative potential of education in reshaping societal attitudes toward environmental conservation, emphasizing the need for sustained investment in educational programs aligned with sustainability goals. By integrating these diverse elements, the research advances theoretical frameworks and offers actionable insights for achieving a sustainable future in resource-rich contexts. The rationale for this analysis stems from the urgent global need to address climate change and promote sustainable development. By investigating the combined effects of these variables, we aim to provide a more comprehensive understanding of the drivers and barriers to achieving SDGs 7 and 13. This multifaceted approach allows us to uncover potential synergies and trade-offs between economic development and environmental conservation. Our findings can inform policymakers in resource-rich nations on effectively leveraging their natural resources, education systems, financial sectors, and technological capabilities to promote sustainable practices while maintaining economic growth. This research fills a gap in the existing literature by offering empirical evidence on the collective influence of these factors on sustainability outcomes, contributing to the development of more holistic and effective strategies for achieving the SDGs.

The rest of the manuscript's structure follows: literature review and hypothesis development are available in Section II. Data, methodology, and estimation strategies are available in Section III. Section IV deals with the model estimation and interpretation, and the discussion of the study findings can be found in Section V. Finally, Section IV reports the conclusion and policy suggestions of the study.

2 Literature survey

2.1 Theoretical review of the study

Sustainable development, progress in the financial sector, and natural resource management all have intricate inter-relationships. Achieving sustainable development objectives and social fairness requires a combination of economic growth, financial development, and social development. The wellbeing of households and their investments may result from a more diverse income stream across resource-rich nations. According to [16], resource-rich nations should aim to broaden their income streams to facilitate long-term financial growth and sustainable progress. Suppose resource-rich

nations want to attract more foreign direct investment (FDI). In that case, they need a strong financial system because, according to the resource curse theory, having too many resources may slow down economic growth. A robust financial system is crucial for resource-rich nations to entice foreign direct investment and foster sustainable development [17].

Research has shown a favourable correlation between financial inclusion (i.e., the availability and use of formal financial services) and environmental sustainability, especially in non-EU nations. [18] argues that resource-rich countries may accomplish sustainable development objectives by combining environmental sustainability initiatives with financial inclusion programs. Financial inclusion and social inclusion—which includes things like fairness, gender parity, and environmental sustainability—form a strong foundation. Sustainable development objectives about gender equality and poverty reduction may be advanced via enhancing financial inclusion and encouraging entrepreneurship [19–21]. Financial inclusion may be advanced by the policies and programs of governments and central banks, which include expanding access to banking, establishing more automated teller machine (ATM) locations, and introducing digital financial services. In order to craft efficient policies, it is essential to measure the extent of financial inclusion, which includes digital components [22]. Many variables affect financial inclusion, such as poverty, the financial system's stability, the economy, financial literacy, and regulatory frameworks, which vary from country to country. The global financial inclusion agenda may benefit from theories of financial inclusion by facilitating relevant debates and problem-solving [23].

Complex and country-specific relationships characterize the connection between financial inclusion and development. Although research has shown that financial inclusion boosts GDP development, the exact nature of this benefit may vary from country to country based on cultural norms and the strength of their financial institutions [24]. Stability in the financial sector and the collection of tax funds are two other potential outcomes of financial inclusion. Some research suggests a link between financial inclusion and better financial stability, and it benefits tax income. [25] found that variables such as differences in national wealth might impact the connection. Because it may improve household well-being and economic growth, financial inclusion is seen as a key tool for reaching the sustainable development objectives set by the United Nations. Policymakers must have multidimensional indices measuring financial inclusion and accounting for accessibility, use, and service quality [26]. Reducing poverty and income inequality are two more potential outcomes of financial inclusion. The impact of financial inclusion on poverty and income inequality in developing nations may be conditional on variables such as financial behaviour and capacity; however, research has shown that it can have this effect [27]. Extensive research on the causes and effects of financial inclusion on development outcomes such as inequality and poverty has yielded contradictory results. Financial inclusion and development may have different relationships depending on country-specific elements, including socio-cultural traits and the quality of institutions [28].

2.2 Financial inclusion led- sustainability

Financial inclusion and environmental sustainability are two significant and progressively prominent topics that have received considerable scholarly attention recently. The expanding corpus of literature that examines the complex interplay between financial inclusion and environmental sustainability highlights its profound importance within academic discourse. Within the scope of this comprehensive review, our objective is to synthesize and critically evaluate the principal findings from a carefully chosen set of studies within this particular field of research. The empirical evidence overwhelmingly supports a strong and positive correlation between financial inclusion and environmental sustainability. This correlation has been consistently demonstrated across multiple studies [29–31]. The findings of these investigations demonstrate that the inclusion of individuals in the financial system enables them to have increased access to a wide range of financial services, which, in turn, leads to a greater propensity to invest in projects that promote environmental sustainability. These investments encompass a diverse range of initiatives, including, but not limited to, ventures in renewable energy, enhancements in energy efficiency, and the promotion of other environmentally friendly endeavors. One crucial aspect of the correlation between financial inclusion and environmental sustainability pertains to eco-innovation facilitation. This emerging field encompasses creating innovative products, services, and processes distinguished by their commitment to environmental sustainability [32]. Financial inclusion plays a crucial role in this context, providing entrepreneurs and innovators with the financial resources to develop and implement innovative ideas that prioritize the environment.

Another line of evidence can be found that the catalyst role of FI for restoring environmental degradation is financial inclusion, which plays a pivotal role in fostering environmental sustainability through its facilitation of accessible and affordable credit schemes for both individuals and businesses, which, in turn, renders investments in green technology more economically viable [33]. Adopting environmentally friendly practices and utilizing green technology within an inclusive financial system have been found to contribute to a notable decrease in greenhouse gas (GHG) emissions, as

highlighted by [34]. However, an accessible financial system can potentially negatively affect environmental quality. The provision of cost-effective financing alternatives has the potential to incentivize and bolster manufacturing and industrial endeavors, thereby leading to a consequential rise in carbon dioxide (CO₂) emissions [35].

2.3 Education-led sustainability

Education is paramount in empowering communities to tackle environmental challenges together effectively. Through promoting collaboration and cooperation among community members, education facilitates the implementation of community-led initiatives to conserve the environment. These initiatives include establishing community gardens, conservation projects, and environmental education programs [36]. Education plays a vital role in developing a competent workforce that can lead the way in transitioning to a more environmentally friendly economy. Education creates job prospects in sectors prioritizing environmental sustainability and resilience by offering training and education in environmental science, sustainable agriculture, and green technology [37].

The study of [38] explored the role of higher education on CO₂ in Turkey for the period 1983–2017 by employing an ARDL-bound testing approach. The study unveiled a catalyst role of education in CO₂ mitigation, especially in the long run. Besides, education is essential for increasing people's understanding of environmental issues and how they can affect ecosystems and human health. By receiving a formal education, individuals learn about subjects like climate change, the loss of biodiversity, and the depletion of resources. This knowledge helps them recognize the significance of environmental sustainability [39]. Education empowers individuals to make well-informed decisions and embrace environmentally friendly behaviors. Through cultivating values centered around conservation and sustainability, education promotes recycling, energy conservation, and responsible consumption, thereby contributing to environmental protection. A higher level of education is linked to the growth of critical thinking skills, which allows individuals to assess environmental issues and potential solutions thoughtfully. Education helps develop analytical thinking and problem-solving abilities, enabling individuals to tackle intricate ecological problems and promote sustainable practices. People with higher levels of education are more inclined to back and engage in environmental policymaking and initiatives. Their understanding of the scientific evidence supporting environmental policies and the advantages they offer enables them to actively participate in advocacy and contribute to the successful implementation of sustainable measures [40]. Education is crucial for promoting innovation and technological progress in sustainability. By focusing on areas like renewable energy, waste management, and green infrastructure, educated individuals can actively contribute to creating and implementing sustainable technologies that help reduce environmental harm [41–44]. Furthermore, educational institutions have the chance to incorporate sustainability principles into their curriculum across different subjects, which can be achieved by offering courses, projects, and initiatives focusing on sustainability. By doing so, education plays a crucial role in preparing future generations with the necessary knowledge and abilities to tackle sustainability issues in various fields, from business to engineering to public policy [45].

2.4 Technological innovation led to sustainability.

Technological innovation has been widely recognized as a significant contributor to financial inclusion (FIN) and environmental sustainability [46]. According to endogenous growth theory and ecological modernization theory, innovation may aid nations in achieving sustainable development without harming the environment. [47, 48]. Some academics contend that technical progress has two sides: it may either exacerbate or mitigate environmental harm. Natural oil and mineral depletion are on the rise because of technological developments that have made it simpler for people to obtain these resources; this has led to an ecological imbalance and increased pollution levels (49), (50), and [49]. Therefore, it is essential to carefully examine the impact of technological innovation on environmental and energy sustainability. While technological innovation can promote renewable energy consumption and reduce the negative impact of natural resource extraction on the environment, it can also lead to environmental degradation if not appropriately managed [50]. Promoting sustainable practices and protecting the environment while promoting technological innovation and financial inclusion is crucial, which can be achieved through education awareness campaigns and policies that promote green openness and sustainable development [51]. By doing so, we can ensure that technological innovation and financial inclusion contribute to environmental and energy sustainability rather than exacerbating environmental problems [52]. Technological innovations in green building design, construction materials, and sustainable architecture promote energy efficiency, water conservation, and indoor environmental quality. Features such as passive solar design, green roofs, recycled materials, and intelligent building systems minimize environmental impacts, enhance occupant comfort,

and reduce operational costs over the building's lifecycle [53]. Advances in circular economy principles and practices facilitate the efficient use, reuse, and recycling of resources and materials. Technologies such as advanced recycling processes, waste-to-energy systems, and product lifecycle management software enable the recovery and repurposing of valuable resources, diverting waste from landfills and reducing resource depletion and environmental pollution [54, 55]. Innovative grid technologies and energy storage systems enhance electricity generation, distribution, and consumption reliability, flexibility, and efficiency. Integration of renewable energy sources, demand-response mechanisms, and grid-scale energy storage solutions optimize energy management, stabilize power grids, and accommodate variable energy production, accelerating the transition to a low-carbon energy future [56]. Summary displayed in Table 1

3 Data and methodology of the study

3.1 Theoretical framework and model specification

This study aims to develop a comprehensive theoretical framework that aims to clarify the complex interconnections and effects of financial inclusion, education, natural resources, and innovation on environmental and energy sustainability. The foundation of our approach lies in a rigorous analysis of the impact of these crucial factors on the two dimensions of sustainability. Financial inclusion plays a crucial role in driving economic development by providing individuals and businesses, as well as tiny and medium-sized enterprises, with the opportunity to access a comprehensive range of financial services labor, Offiong [76]. The inclusive financial ecosystem has the potential to stimulate eco-innovation and promote sustainable development [77]. However, it is essential to recognize that within the context of economic globalization and climate change, financial inclusion may unintentionally hinder the overall objective of achieving sustainable development [78]. Hence, we must thoroughly evaluate the intricate impact of financial development and financial inclusion on enhancing environmental and energy sustainability [79]. Similarly, technological innovation arises as a significant force, exerting substantial influence in advancing environmental and energy sustainability [80, 81]. The ongoing progress in technology plays a crucial role in facilitating the growth and widespread adoption of environmentally sustainable solutions and practices. Educational initiatives are crucial in our collective efforts to achieve environmental and energy sustainability. Education plays a crucial role in promoting sustainable behaviors and raising awareness by facilitating the dissemination of knowledge and fostering environmental consciousness [82].

Including natural resources introduces a layer of intricacy to the multifaceted framework of sustainability dynamics. Utilizing these resources can drive economic growth; however, their unregulated exploitation can harm the environment and energy resources [83, 84]. Therefore, it is crucial to thoroughly analyze the interdependent connection between natural resources and economic growth and investigate the potential of combining green innovation and financial inclusion to foster sustainable economic expansion [85]. Furthermore, using renewable energy has emerged as a crucial element in the ongoing discussion regarding environmental and energy sustainability. The adoption of renewable energy sources not only serves to mitigate CO₂ emissions but also facilitates the promotion of sustainable energy practices [80]. Therefore, conducting a comprehensive assessment of the combined impact of financial inclusion, education, natural resources, and innovation on the consumption of renewable energy is crucial. This evaluation aims to determine their potential contribution to the overarching goals of environmental and energy sustainability [86].

The motivation of the study is to assess the critical role of natural resources, education, and access to financial services in achieving SDGs 7–13 in the top 8 resource-based nations for the period 2004–2022. In this study, we considered two variables in measuring SDGs 7 and 13 with clean energy consumption and climate change with CO₂ emission. The generalized empirical equation is as follows.

$$\text{For SDGs 07 : REC} | \text{NRR, FI, EDU} \quad (1)$$

$$\text{For SDGs 13 : CO}_2 | \text{NRR, FI, EDU} \quad (2)$$

Addressing the existing literature, the present study has expanded the above equation by including technological innovation, which has emerged as a catalyst variable in achieving the SDGs and getting critical attention. Thus, the revised Eqs. (1) and (2) are displayed in the following

Table 1 Summary of literature survey

Element	Findings	Reference
Technological Innovation	Technological innovation contributes to environmental sustainability by reducing CO2 emissions by developing and adopting green technologies	Ahmad, Ahmed [46]; Iqbal, Khan [48]; Gao, Wang [57]
	Innovation may also have adverse effects by making natural resource extraction more efficient, potentially increasing environmental degradation	Ibrahim, Ajide [58]
	Innovations in energy efficiency, renewable energy technologies, and green building designs significantly contribute to reducing carbon footprints	Chel and Kaushik [53]; Ayres and Ayres [59]& Anser, Iqbal [60]
	Green innovation is crucial for mitigating adverse environmental impacts and promoting sustainable energy practices	Bilgili, Önderol [11]
Education	Higher education and awareness significantly reduce CO2 emissions and ecological footprints by promoting sustainable practices and environmental stewardship	Msengi, Doe [61]; Generous [62]; Anderson [14],
	Education can also foster innovation and the adoption of green technologies, playing a vital role in environmental sustainability	Alibašić [63],, Yu [64]; Wu, Wan [65]
	Environmental education is essential for developing pro-environmental behaviors and attitudes, supporting energy-efficient products, and promoting green consumption	Wang, Sun [66]; Zheng, Umar [67]; Hamzah and Tanwir [68]& Hamzah and Tanwir [68]
Natural Resources	Exploiting natural resources often leads to higher CO2 emissions due to energy-intensive economic activities	Bekun, Aloba [69]; Huang, Sadiq [70]
	Proper management and regulation of natural resource use can mitigate environmental degradation and support sustainable development	Damrah, Satrovic [71]; Sun, Chenggang [72]
	Natural resources can also facilitate the adoption of renewable energy consumption, contributing to energy sustainability	Zhang and Chen [73]; Han, Zakari [74]; Kwakwa [75]

$$\text{For SDGs 07 : REC} | \text{NRR, FI, EDU, INNO} \quad (3)$$

$$\text{For SDGs 13 : CO}_2 | \text{NRR, FI, EDU, INNO} \quad (4)$$

After the log transformation, the above equation can be expressed in the regression equation in the following manners.

$$REC = \beta_0 + \beta_1 \text{NRR} + \beta_2 \text{FI} + \beta_3 \text{EDU} + \beta_4 \text{INNO} + \varepsilon \quad (5)$$

$$\text{CO}_2 = \gamma_0 + \gamma_1 \text{NRR} + \gamma_2 \text{FI} + \gamma_3 \text{EDU} + \gamma_4 \text{INNO} + \varepsilon \quad (6)$$

In these regression equations: The dependent variables are REC and CO₂, representing the outcomes or targets related to SDGs 7 and 13, respectively. The independent variables are NRR, FI, EDU, and INNO, which are assumed to influence the dependent variables. The regression coefficients (β and γ) represent the expected change in the dependent variable for a unit change in the corresponding independent variable, holding all other variables constant. The error term (ε) accounts for the unexplained variation in the dependent variable that is not captured by the independent variables in the model.

3.2 Variable definition and expected sign

Energy and environmental sustainability are critical concepts in sustainable development, with various studies providing insights into their definitions and proxy variables used for their assessment. Energy Sustainability is the capacity to harness sustainable energy sources and carriers, enhance efficiency, reduce environmental impact, and improve socioeconomic acceptability [87]. It is a multifaceted concept that involves technological, environmental, and socioeconomic issues. Proxy variables for energy sustainability include environmental indicators, human system factors, and energy system indicators [88]. These factors collectively address the sustainable utilization of energy resources, economic affordability, and minimization of adverse environmental impacts. Moreover, sustainable energy emphasizes adopting renewable energy sources and energy efficiency as pivotal components for achieving a sustainable energy system.

Environmental Sustainability concerns the measures undertaken to decrease the environmental impact of energy sectors, focusing on carbon emissions reduction, renewable energy adoption, and energy efficiency [88]. Proxy variables for environmental sustainability include carbon emissions, air, and water quality, biodiversity conservation [89], and the emphasis on maintaining ecosystem health and biodiversity over the long term [90]. These variables highlight the importance of preserving natural resources and ensuring the health of ecosystems for future generations. The research underscores the significance of utilizing renewable energy and enhancing energy efficiency as crucial for advancing energy sustainability. Simultaneously, it advocates for reducing carbon emissions and safeguarding biodiversity as essential measures for fostering environmental sustainability. Together, these efforts aim to balance the fulfillment of current needs without jeopardizing the ability of future generations to meet theirs, thereby ensuring the sustainability of energy systems and the environment.

Our first independent variable is natural resource rent (NRR), which is the exploitation of natural resources that can result in higher CO₂ emissions due to the promotion of energy-intensive economic and industrial activities that heavily rely on fossil fuels. Nevertheless, the influence of natural resource rent on CO₂ emissions may differ based on the country's economic structure, the specific type of natural resources involved, and the environmental policies that have been implemented. In Pakistan, using natural resources contributes to the acceleration of CO₂ emissions, leading to a decline in environmental quality. However, urbanization has a positive impact on environmental quality as it helps mitigate CO₂ emission levels, as stated by [91]. In the context of Belt and Road Initiative (BRI) countries, it is worth noting that the CO₂ emissions associated with natural resource-based activities can be influenced by natural resource rent, as highlighted by a study conducted by [72].

Our second variable is education, measured by governmental investment in education as a % of GP. Although there is no explicit mention of studies connecting education to CO₂ emissions, it is widely recognized that education can significantly raise public awareness about environmental concerns, advocate for sustainable practices, and foster green technologies' advancement [92]. Well-informed individuals are more adept at recognizing the significance of decreasing CO₂ emissions and are more inclined to endorse policies and practices that foster environmental sustainability [93].

Our third explanatory variable is financial services. Extensive research has shown that in certain situations, the expansion of financial services can have a notable impact on CO₂ emissions, which implies that while access to financial

services is crucial, it must be accompanied by sustainable investment practices to prevent environmental degradation [94]. Moreover, financial inclusion plays a crucial role in facilitating the acquisition of capital for investments in renewable energy and energy efficiency projects, which has the potential to effectively reduce CO₂ emissions, especially when these investments are aligned with sustainable development goals [95].

Finally, the fourth explanatory variable is technological innovation, crucial in reducing CO₂ emissions. Specifically, advancements in carbon capture and utilization, renewable energy sources, and energy efficiency have the potential to make a significant impact [96]. The emergence of carbon capture and utilization technologies represents a significant change in how we view CO₂. It reflects a growing recognition of the need to address environmental pollution and the depletion of traditional carbon resources [97]. Researchers have highlighted the potential of these technologies in creating new CO₂-based markets and industries. The importance of technological advancements in renewable energies, including solar, wind, hydro, geothermal, and biomass energy sources, cannot be overstated. These advancements are vital in reducing CO₂ emissions and enhancing air quality. Experts in this field have conducted extensive research to understand the potential of these energy sources and their impact on the environment. The findings highlight the significance of embracing renewable energies as a sustainable solution for our energy needs. Table 2 summarizes the variables, their proxies, and the expected signs based on the literature:

3.3 Estimation strategies

Consider the weighted CD test statistic and assume that the following two points hold.

$$CD_W = \left(\frac{1}{NT} \sum_{i=1}^N \sum_{t=1}^T \hat{\varepsilon}_{i,t}^2 w_i^2 \right)^{-1} \left(\sqrt{\frac{2}{TN(N-1)}} \sum_{t=1}^T \sum_{i=2}^N \sum_{j=1}^{i-1} w_i \hat{\varepsilon}_{i,t} w_j \hat{\varepsilon}_{j,t} \right) \quad (7)$$

Under either of the two sets of assumptions above,

$$CD_W \xrightarrow{d} N(0, 1)$$

as $N, T \rightarrow \infty$ jointly subject to the restriction $\sqrt{TN}^{-1} \rightarrow 0$

The slope of heterogeneity test:

Consider the classical panel-data model with heterogeneous slopes-

$$y_{i,t} = \mu_i + \beta_{1i}' x_{1i,t} + \beta_{2i}' x_{2i,t} + \varepsilon_{i,t} \quad (8)$$

where $i = 1, \dots, N$ represents the cross-sectional dimension and $t = 1, \dots, T$ the time dimension. μ_i It is a unit-specific constant. β_{1i} is $k_1 \times 1$, β_{2i} is $k_2 \times 1$, and both are vectors of unknown slope coefficients with $k = k_1 + k_2$ being the total number of regressors. $x_{1i,t}$ is a $k_1 \times 1$ vector, and $x_{2i,t}$ a $k_2 \times 1$ vector containing strictly exogenous regressors.

3.3.1 Null hypothesis for slope homogeneity test

$$H_0 : \beta_{2i} = \beta_2 \text{ for all } i$$

Table 2 Proxies and expected to sing on ES

Variable	Proxy	Expected Sign
Natural Resource Rent	Exploitation of natural resources	Positive (+) on CO ₂ emissions
Education	Governmental investment in education as % of GDP	Negative (–) on CO ₂ emissions
Financial Services	Access to financial services, sustainable investment practices	Negative (–) on CO ₂ emissions if aligned with SDGs; Positive (+) otherwise
Technological Innovation	Advancements in carbon capture, renewable energy sources, and energy efficiency	Negative (–) on CO ₂ emissions

3.3.2 Alternative hypothesis for slope heterogeneity

$$H_A : \beta_{2i} \neq \beta_2 \text{ for some } i$$

Pesaran [98],

Typically, the presence of a unit root in panel data is examined using second-generation panel unit root tests like CADF (cross-sectionally augmented Dickey-Fuller) and CIPS (cross-sectionally augmented IPS). An analogous method of assessment has been used in the present investigation. By supplementing the IPS test with additional lagged levels of the dependent variable, the CIPS test tackles the problem of cross-sectional dependence in panel data. This approach is useful for handling the likely existence of correlation among the different units in the panel correctly. Incorporating cross-sectional averages of lagged values of the dependent variable, the CADF test improves upon the Dickey-Fuller test.

$$\Delta Y_{it} = \beta_i + \gamma_i Y_{i,t-1} + \pi_i \bar{Y}_{t-1} + \beta_i \bar{Y}_t + \rho_{it} \quad (9)$$

$$\Delta Y_{it} = \mu_i + \gamma_i Y_{i,t-1} + \pi_i \bar{Y}_{(t-1)} + \sum_{k=1}^p \beta_{ik} \Delta Y_{i,k-1} + \sum_{k=0}^p \beta_{ik} \Delta \bar{Y}_{i,k-0} + \alpha_i t \quad (10)$$

$$CIPS = N^{-1} \sum_{i=1}^N \partial_i(N, T) \quad (11)$$

$$CIPS = N^{-1} \sum_{i=1}^N CADF \quad (12)$$

Westerlund [99] [100] examined the relationship between variables over time using a panel cointegration test. Additionally, they used Westerlund's error correction-based cointegration test in their research. The study aimed to test the null hypothesis that no cointegration occurred using two sets of test statistics.

$$\Delta Z_{it} = \partial_i d_i + \theta_i \left(Z_{i,t-1} - \delta_i W'_{i,t-1} \right) + \sum_{r=1}^p \theta_{i,r} \Delta Z_{i,t-r} + \sum_{r=0}^p \gamma_{i,j} \Delta W_{i,t-r} + \varepsilon_{i,t} \quad (13)$$

$$G_T = \frac{1}{N} \sum_{i=1}^N \frac{\varphi_i}{SE \varphi_i} \quad (14)$$

$$G_T = \frac{1}{N} \sum_{i=1}^N \frac{T \varphi_i}{\varphi_i(1)} \quad (15)$$

$$P_T = \frac{\varphi_i}{SE \varphi_i} \quad (16)$$

$$P_a = T \varphi_i \quad (17)$$

Cointegration analysis is integral to examining long-run equilibrium relationships among variables. The study adopts second-generation panel cointegration tests, such as those introduced by Westerlund and Pedroni, which address cross-sectional dependency—a limitation in earlier, first-generation methods. These tests are particularly relevant given the global environmental and economic variables interlinkages. Using cointegration ensures that the long-term dynamics are not overlooked, providing a comprehensive understanding of how variables co-evolve over time.

This research employed the suggested Dynamic Seemingly Unrelated Regression (DSUR) estimator to determine how independent factors affected dependent variables. The DSUR method works for balanced panels with fewer time-series data T and fewer co-integrating regression equations N . Here are the components that make up the model:

$$y_{it} = \beta_i x_{it} + u_{it}^{\dagger} \quad (18)$$

$$u_{it}^{\dagger} = \rho_i u_{it-1}^{\dagger} + \sum_{j=1}^{n-1} \delta_{ij} \Delta x_{it-1} + \omega_{it} \quad (19)$$

$$\Delta x_{it} = \varnothing_i \Delta x_{it-1} + m_{it} \quad (20)$$

$$\omega_{it} = \lambda_i \theta_t + \xi_{it} \quad (21)$$

The bias-corrected Cup estimator is defined as –

$$\hat{\beta}_{CupBC} = \hat{\beta}_{Cup} - \frac{1}{T} \hat{\phi}_{nT} \quad (22)$$

where

$$\hat{\phi}_{nT} = \left[\frac{1}{nT^2} \sum_{i=1}^n \hat{Z}_i' \hat{Z}_i \right]^{-1} \left(\frac{1}{n} \sum_{i=1}^n \hat{\theta}_i \right) \quad (23)$$

$$\hat{\theta}_i = \hat{Z}_i' \Delta \hat{b}_i \hat{\Omega}_{bi}^{-1} \hat{\Omega}_{bui} \left(\hat{\Delta}_{\varepsilon ui}^+ - \hat{\delta}_i' \hat{\Delta}_{nu}^+ \right)$$

$$\hat{\delta}_i = \left(\hat{F}' \hat{F} \right)^{-1} \hat{F}' \hat{x}_i \Delta \hat{b}_i = \left(\Delta \hat{x}_i \Delta \hat{F} \right) \quad (24)$$

$$\hat{\hat{x}}_i = x_i - \frac{1}{n} \sum_{k=1}^n x_{kt} \hat{a}_{ik}, \hat{a}_{ik} = \hat{\lambda}_i' \left(\hat{\Lambda}' \hat{\Lambda} / n \right)^{-1} \hat{\lambda}_k$$

Assuming as $(n, T) \rightarrow \infty$ with $n/T \rightarrow 0$,

$$\sqrt{nT} \left(\hat{\beta}_{CupBC} - \beta^0 \rightarrow N(0, \Sigma) \right)$$

The CupBC is $\sqrt{nT}$ consistent with a limiting distribution that is centered at zero as long as $(n, T) \rightarrow \infty$ and $n/T \rightarrow 0$.

$$\hat{\beta}_{CupFM} = \left(\sum_{i=1}^n x_i' M_{\hat{F}} x_i \right)^{-1} \sum_{i=1}^n \left(x_i' M_{\hat{F}} y_i^+ - T \left(\hat{\Delta}_{\varepsilon ui}^+ - \hat{\delta}_i' \hat{\Delta}_{nu}^+ \right) \right) \quad (25)$$

$$\Delta y_{it} = \alpha_i + \beta_i \Delta x_{it} + \sum_{t=1}^T \theta_t D_t + \varphi_i f_t + \varepsilon_{it} \quad (26)$$

Δ denotes the first-difference operator, β_i indicates the country-specific coefficients, and θ_t describes the coefficients of the time dummies.

The AMG estimator is then obtained from the across-panel averaged group-specific parameters:

$$AMG = \frac{1}{N} \sum_{i=1}^N \tilde{\beta}_i \quad (27)$$

Dynamic panel data models are particularly suited for addressing endogeneity issues and capturing the temporal dynamics of the variables. The study uses techniques such as the Dynamic Seemingly Unrelated Regression (DSUR) and the Augmented Mean Group (AMG) estimator, which are well-suited for panel datasets with heterogeneous

slopes. Unlike fixed or random effects models, these approaches account for heterogeneity across countries, enabling a more nuanced analysis of resource-rich nations. The AMG estimator also incorporates cross-sectional dependence, a common issue in panel data involving macroeconomic and environmental variables.

None of the above estimators allows for heterogeneity in the slopes. Pesaran and Smith [101] propose an MG approach by estimating individual (OLS) equations.

$$y_{it} = \alpha_i + \beta_i x_{it} + e_{it}, e_{it} \sim iid(0, \sigma_i^2),$$

Furthermore, define the estimator. $\hat{\beta}^{MG} = N^{-1} \sum_{i=1}^N \hat{\beta}_i$ with variance $V(\hat{\beta}^{MG}) = \frac{1}{N(N-1)} \sum_{i=1}^N (\hat{\beta}_i - \bar{\beta})^2$.

Our study would benefit from using the Nonlinear Autoregressive Distributed Lag (NARDL) model to examine the connections between green innovation, green energy, and tourism. One of the most important things about the NARDL model is that it can capture both short- and long-run dynamics. This is important for understanding how tourism might affect environmental sustainability via innovation and green energy. To capture the non-linearities in the relationships, the study employs the Nonlinear Autoregressive Distributed Lag (NARDL) model. This innovative approach distinguishes between positive and negative changes in independent variables, enabling the analysis of asymmetric effects. For instance, the impact of an increase in natural resource rents on CO2 emissions might differ significantly from that of a decrease. By incorporating asymmetries, the study uncovers deeper insights into how different shocks influence sustainability outcomes, which symmetric models would miss.

$$\begin{aligned} \ln CO2_{it} = & \alpha_0 + \sum_{j=1}^{q^1j} \gamma_{ij} \ln CO2_{i(t-j)} + \sum_{j=0}^q \gamma_{1j} \ln NRR_{i(t-j)} + \sum_{j=0}^q \gamma_{2j} \ln FI_{it-j} \\ & + \sum_{j=0}^q \gamma_{3j} \ln EDU_{it-j} + \sum_{j=1}^{q^1j} \theta_{ij} \ln \overline{CO2}_{i(t-j)} + \sum_{j=0}^q \theta_{1j} \ln \overline{NRR}_{i(t-j)} \\ & + \sum_{j=0}^q \theta_{2j} \ln FI_{it-j} + \sum_{j=0}^q \theta_{3j} \ln \overline{EDU}_{it-j} + \varepsilon_{it-j} \end{aligned} \quad (28)$$

$$\begin{aligned} \ln REC_{it} = & \alpha_0 + \sum_{j=1}^{q^1j} \gamma_{ij} \ln REC_{i(t-j)} + \sum_{j=0}^q \gamma_{1j} \ln NRR_{i(t-j)} + \sum_{j=0}^q \gamma_{2j} \ln FI_{it-j} \\ & + \sum_{j=0}^q \gamma_{3j} \ln EDU_{it-j} + \sum_{j=1}^{q^1j} \theta_{ij} \ln \overline{REC}_{i(t-j)} + \sum_{j=0}^q \theta_{1j} \ln \overline{NRR}_{i(t-j)} \\ & + \sum_{j=0}^q \theta_{2j} \ln FI_{it-j} + \sum_{j=0}^q \theta_{3j} \ln \overline{EDU}_{it-j} + \varepsilon_{it-j} \end{aligned} \quad (29)$$

To ensure the reliability of the results, the study integrates multiple estimation techniques, including the Cross-Sectionally Augmented Dickey-Fuller (CADF) and Cross-Sectionally Augmented IPS (CIPS) unit root tests. These methods are particularly robust in addressing cross-sectional dependency. Furthermore, the study employs robustness checks through the Common Correlated Effects Mean Group (CCMG) estimator, ensuring that the findings remain consistent across different modeling frameworks.

Compared to traditional regression models, the selected methodologies provide several advantages. While ordinary least squares (OLS) and fixed/random effects models are simpler, they fail to account for cross-sectional dependence, heterogeneity, and non-linear dynamics. Similarly, first-generation panel unit root and cointegration tests often assume cross-sectional independence, which is unrealistic in a globally interconnected context. The methods used in this study overcome these limitations by explicitly modeling heterogeneity, dependence, and asymmetries, thereby offering a more realistic and accurate representation of the relationships. The methodological innovations in this study contribute to the existing literature by offering a more nuanced framework for analyzing the interplay between natural resources, education, financial inclusion, and technological innovation. By combining advanced panel data techniques with asymmetric modeling, the research captures the general trends and the

Table 3 Results of cross-sectional dependency and slop of heterogeneity test

		LM_{PS}	LM_{adj}	CD_{PS}	Δ	Adj Δ
CO2	366.791***	29.985***	241.777***	19.839***	81.814***	123.03***
REC	246.292***	24.757***	129.76***	10.464***	88.553***	122.307***
FI	286.644***	42.498***	229.506***	12.116***	88.203***	91.478***
TI	289.948***	18.827***	202.214***	47.678***	19.757***	82.588***
NRR	400.281***	31.619***	142.901***	10.103***	22.834***	127.861***
EDU	340.092***	40.897***	135.192***	30.027***	31.179***	119.803***

The superscript of *** denotes the level of significance at a 1% level

Table 4 Second generation panel unit root test

Variables	CADF test statistic		CIPS test statistic		CADF test statistic		CIPS test statistic	
	for constant		for constant		for constant & and trend		for constant & and trend	
	Level	first difference	Level	first difference	level	first difference	level	first difference
CO2	-1.838	-3.023***	-2.325	-2.424***	-1.656	-7.085***	-2.73	-3.047***
REC	-1.152	-4.567***	-2.957	-7.106***	-1.851	-3.826***	-1.122	-4.026***
FI	-2.917	-4.881***	-1.167	-3.597***	-2.966	-5.58***	-2.552	-7.946***
TI	-1.076	-4.863***	-1.967	-5.146***	-2.113	-2.924***	-2.054	-2.208***
NRR	-1.993	-4.531***	-2.729	-6.489***	-2.911	-4.829***	-1.033	-4.477***
EDU	-2.883	-3.567***	-1.046	-6.003***	-1.958	-2.913***	-1.587	-2.606***

the superscript of *** denotes the level of significance at a 1% level

unique, context-specific dynamics that characterize resource-rich nations. This integrative approach enhances the robustness of the findings and sets a methodological benchmark for future studies in the field.

4 Estimation and interpretation

Table 3 displays the results of the heterogeneity and cross-sectional dependency test by following the framework introduced by Breusch and Pagan [102], Pesaran, Ullah [103], Pesaran [104], Pesaran [105] and Pesaran and Yamagata [106]. Referring to the test statistics, it is apparent the rejection of null of “homogeneity” and cross-sectional independence.” The findings suggest the presence of heterogeneity and variables sharing a common dynamic.

Following Pesaran [98], the study executed the second-generation panel unit root test, and the results are reported in Table 4. It is evident that after the first difference operation, the variables become stationary, suggesting the integration order, i.e., $I(1)$.

Prior to executing the target empirical test, the study investigated the presence of a long-run association between dependent and independent variables through the execution of the panel cointegration test introduced by Westerlund [100], Pedroni [107], Pedroni [108], Kao [109]. The output of the panel cointegration test was reported in Table 5, and it found that all the test statistics are statistically significant at a 1% level, unveiling the availability of long-run linkage in the empirical nexus.

Table 6 displays the results of empirical model estimation using DSUR, CUP-FM, and CUP-BC. The coefficients of NRR derived from DSUR, CUP-FM, and CUP-BC unveiled positive statistical significance to ED, which is a proxy by CO₂, implying the extraction of natural resources accelerated the emission of CO₂ in the environment and fostered environmental degradation. Our study findings align with [72] and [91]. However, a contrasting view can be found in the studies of [110] and [111]. Literature argued that the presence of natural resource rents could exert a substantial influence on CO₂ emissions, implying that implementing renewable energy in countries that heavily rely on natural resources has effectively reduced the harmful effects of natural resource rent on CO₂ emissions [69, 70]. The transition to renewable energy sources has the potential to decrease greenhouse gas emissions and effectively combat climate change significantly.

Table 5 Results of the cointegration test

Model	[1]				[2]			
	NNR→ES	FI→ES	EDU→ES	INNO→ES	NNR→ES	FI→ES	EDU→ES	INNO→ES
Gt	− 13.529***	− 4.164***	− 10.723***	− 6.59***	− 13.222***	− 5.82***	− 9.314***	− 10.783***
Ga	− 10.101***	− 8.82***	− 11.048***	− 11.969***	− 13.518***	− 4.282***	− 9.812***	− 10.103***
Pt	− 13.935***	− 6.737***	− 8.459***	− 10.615***	− 14.603***	− 8.017***	− 7.684***	− 10.224***
Pa	− 10.293***	− 9.712***	− 12.447***	− 14.262***	− 14.243***	− 14.117***	− 12.915***	− 7.793***
KRCPT								
MDF	7.757***	− 6.232***	16.335***	1.298***	22.989***	15.619***	10.696***	5.678***
DF	5.158***	− 7.787***	17.854***	2.89***	13.076***	− 4.787***	− 2.985***	22.255***
ADF	− 1.944***	19.305***	7.337***	19.378***	17.035***	2.105***	19.889***	15.951***
UMDF	11.158***	15.935***	− 1.069***	− 7.683***	19.549***	12.667***	12.559***	18.651***
UDF	9.281***	2.401***	14.388***	0.996***	− 1.86***	7.086***	20.566***	20.315***
PCT								
MDF	9.594***	5.937***	− 3.751***	12.659***	4.737***	12.741***	− 7.571***	8.164***
PP	11.353***	7.038***	13.37***	9.305***	11.063***	1.313***	− 5.13***	6.439***
ADF	15.89***	14.291***	9.929***	12.883***	14.117***	8.56***	14.017***	10.603***

the superscript of *** denotes the level of significance at a 1% level

Table 6 Results of DSUR, CUP-FM, and CUP-BC for environmental sustainability

	DSUR			CUP-FM			CUP-BC		
	Coefficient	Std. Error	t-Statistic	Coefficient	Std. Error	t-Statistic	Coefficient	Std. Error	t-Statistic
NNR	0.1776***	0.0411	4.3211	0.1557***	0.023	6.7721	0.1791***	0.0401	4.4663
FI	0.0844***	0.0151	5.5913	0.1517***	0.0195	7.7815	0.1608***	0.0346	4.6512
EDU	− 0.1243***	0.0304	− 4.0911	− 0.1291***	0.0327	− 3.9489	− 0.0802***	0.0244	− 3.2868
INNO	− 0.1403***	0.0351	− 3.9985	− 0.1211***	0.0294	− 4.1204	− 0.0805**	0.0362	− 2.2248
C	14.972***	0.2401	62.3495	17.941***	0.2401	74.7137	13.157***	0.2401	54.7911
R ²	0.908			0.908			0.8859		
Adj R ²	0.9275			0.926			0.9418		

The superscript of *** and ** denote the level of significance at a 1% and 5% level

Referring to the coefficients of financial inclusion (FI), it is divulged that there is a positive linkage to environmental degradation; that is, FI fosters the excessive emission of CO₂ in the ecosystem. Our findings are in line with [112, 113]. These findings support the theory that financial inclusion may influence the environment negatively by granting easy accessibility to financial products and services, advocating that the inclusion of the financial sector increases the consumption of energy-intensive goods, resulting in more environmental emissions [71]. Besides, in many cases, financial inclusion can be a good stimulus for an enterprise to accelerate its production rate, which also causes the growth in pollutant emissions and adverse environmental effects. In conclusion, it would be argued that the literature supports that financial inclusion builds a process or an effect that results in excessive CO₂ emission into the ecosystem. Literature posted by Khan, Yan [113], Qamruzzaman [114], Qamruzzaman and Karim [115] This is quite obvious since financial inclusion can bring in economic activities that will need more energy and thus produce more CO₂ into the atmosphere. With its benefits, financial inclusion has its upshots, though its improvement might bring with it potential negative impacts on the environment if not well controlled.

Toe sign of education coefficients in three techniques revealed negative statistical significance at a 1% level, suggesting that an increase in education level, which is measured by enrollment in secondary schooling, in the economy uplifts the process of environmental sustainability, which is in line with [65, 116, 117] Results suggest that an increase in education level, as measured by enrollment in secondary schooling, can have both positive and negative effects on environmental sustainability. On the positive side, education can encourage pro-environmental behaviors and attitudes, support energy-efficient products, and promote investments in green technologies. Additionally, environmental education can

Table 7 Results of DSUR, CUP-FM, and CUP-BC for Energy Sustainability

	Coefficient	Std. Error	t-Statistic	Coefficient	Std. Error	t-Statistic	Coefficient	Std. Error	t-Statistic
DSUR	CUP-FM			CUP-BC			DSUR		
NRR	− 0.0823***	0.0272	− 3.0275	− 0.0878***	0.0161	− 5.4534	− 0.1246***	0.0257	− 4.8505
FI	0.1476***	0.0265	5.5724	0.1720***	0.0381	4.5162	0.1348***	0.0151	8.9271
EDU	0.1374***	0.028	4.9096	0.1165***	0.0233	5.0030	0.0964***	0.0343	2.9151
INNO	0.1031***	0.0327	3.1541	0.1554***	0.0429	3.6244	0.1289***	0.0261	4.9398
C	16.951***	0.24013	70.5867	16.254***	0.24013	67.6883	15.536***	0.2401	64.6982
R2	0.9			0.9033			0.8963		
Adj R ²	0.9475			0.9484			0.9511		

The superscript of *** and ** denote the level of significance at a 1% and 5% level

improve environmental quality through green consumption and pollution control. Furthermore, education can play a crucial role in shaping societal environmental awareness and culture, which is essential for effectively addressing environmental problems.

Finally, the effects of technological innovation are negatively connected to CO₂ emission, which is predominately established in the literature [118–120], and [121]. The study of Chen and Lee (2020) conducted cross-country research that indicates technological innovation can significantly reduce CO₂ emissions in resource-dependent countries, while Du et al. (2019) found that green technology innovations contribute to carbon dioxide emission reduction based on patent data. Gao, Wang [57] investigated the impact of innovation on CO₂ emissions, showing that R&D spending can have a positive effect on reducing emissions. [121] compared the effects of technological innovation on CO₂ emissions between China and India, revealing that innovation can play a crucial role in reducing emissions. [122] studied the impact of innovation and technology investments on carbon emissions in selected OECD countries, further emphasizing the role of technological innovation in reducing emissions. [123] explored the relationship between green growth, environmental taxes, renewable energy, and human capital in G7 countries, highlighting the importance of technological innovation in promoting low carbon emissions.

For energy sustainability through the inclusion of renewable sources, the study disclosed an adverse association between NRR and REC in all three methods (see Table 7); that is, NRR discourages the consumption of RE over fossil fuel. The existence of natural resource rent poses a major barrier to the global transition towards sustainable energy by impeding the growth of Renewable Energy Consumption (REC). Exploiting non-renewable resources, such as oil, minerals, and gas, may create cash that fosters an economic dependence and supports the existing energy production and consumption level. Consequently, this leads to a shift of focus and allocation of resources away from investments in renewable energy infrastructure and technologies [124]. The emphasis on short-term gains obtained from exploiting natural resources may lead to a neglect of investment in renewable energy sources, which are essential for attaining sustainable and enduring economic progress. When governments or corporations prioritize the immediate economic benefits derived from their natural resource revenues, they are less inclined to dedicate resources towards investments in renewable energy. This scenario perpetuates dependence on non-renewable fuels, hindering the advancement towards embracing cleaner and more sustainable energy sources. This shift is crucial because it tackles environmental issues and the need for energy security and economic resilience in the face of depleting natural resources.

Following this, the asymmetric investigation was performed using a nonlinear framework. Table 8 displays the results of asymmetric coefficients exhibiting the positive negative shock of NRR, FI, and EDU on environmental sustainability.

The long-run results indicate a significant positive impact of positive shocks in natural resource rent (NRR⁺) on CO₂ emissions, with a coefficient of 0.2885, suggesting that increases in natural resource rents lead to higher CO₂ emissions. Conversely, negative shocks in NRR (NRR⁻) also positively impact CO₂ emissions but to a lesser extent, with a coefficient of 0.2438. This indicates that both increases and decreases in natural resource rents contribute to environmental degradation, though the impact of positive changes is more pronounced. Financial inclusion (FI⁺) similarly exhibits a positive correlation with CO₂ emissions, with a coefficient of 0.1723, implying that increased access to financial services fosters environmental degradation. Notably, the negative shocks in financial inclusion (FI⁻) have an even higher coefficient of 0.2111, underscoring that reductions in financial inclusion exacerbate CO₂ emissions significantly. Education (EDU⁺) and technological innovation (TI⁺) both exhibit negative coefficients of -0.2562 and -0.1835, respectively, indicating that increases in education and technological innovation significantly reduce CO₂ emissions. Interestingly, the negative

Table 8 Results of asymmetric coefficients

Variables	Long-run results			Short-run results		
	Coefficient	st.error	t-stat	Coefficient	st.error	t-stat
Panel –A: environmental sustainability measured by CO ₂						
NRR ⁺	0.2885***	0.0279	10.341	0.0542***	0.0042	12.9047
NRR ⁻	0.2438***	0.0854	2.8548	0.0849	0.0552	1.5384
FI ⁺	0.1723***	0.0354	4.8672	0.0621	0.0444	1.3986
FI ⁻	0.2111***	0.0298	7.0839	0.0646	0.0676	0.9556
EDU ⁺	– 0.2562***	0.0189	13.556	– 0.0732***	0.0053	13.8113
EDU ⁻	– 0.1798***	0.0083	– 21.663	– 0.0911*	0.0486	1.8724
TI ⁺	– 0.1835***	0.0026	70.577	– 0.0823***	0.0286	2.8776
TI ⁻	– 0.2716***	0.0109	24.917	– 0.0774***	0.0104	7.4423
C	0.2644***	0.0259	10.208			
cointEq (-1)				– 0.4746***	0.0804	– 5.9032
Panel –B: energy sustainability measured by REC						
NRR ⁺	– 0.1692***	0.0302	– 5.6026	– 0.0906***	0.0092	– 9.8478
NRR ⁻	– 0.1174***	0.0138	– 8.5072	– 0.0942	0.0608	– 1.5493
FI ⁺	0.1764***	0.0062	28.4516	0.0675***	0.0196	3.4438
FI ⁻	0.1709***	0.0206	8.2961	0.0899***	0.0026	34.577
EDU ⁺	0.1633***	0.0062	26.3387	0.0707***	0.0186	3.8018
EDU ⁻	0.1115***	0.0209	5.3349	– 0.0839***	0.0251	– 3.3426
TI ⁺	0.2968***	0.0477	6.2222	0.0462***	0.0081	5.7037
TI ⁻	0.1705***	0.0548	3.1113	0.0665	0.0649	1.0246
cointEq (-1)				– 0.4978***	0.0108	– 46.096
Long-run and short-run symmetry test						
W_{NRR}^{LR}	9.218			9.482		
W_{NRR}^{SR}	14.567			10.865		
W_{FI}^{LR}	13.975			8.908		
W_{FI}^{SR}	14.899			12.153		
W_{EDU}^{LR}	12.905			12.131		
W_{EDU}^{SR}	12.651			13.734		
W_{TI}^{LR}	14.022			14.945		
W_{TI}^{SR}	9.554			10.209		

Note: the superscript of *** /**/* denote the level of significance at a 1%,5%, 10% respectively

shocks in education (EDU⁻) and technological innovation (TI⁻) also show negative coefficients, suggesting that even reductions in these variables contribute to environmental improvements. However, the magnitude of these impacts is slightly lower than their positive counterparts.

In the short-run results, positive shocks in natural resource rent (NRR⁺) continue to positively impact CO₂ emissions, with a coefficient of 0.0542, indicating that short-term increases in natural resource rents contribute to higher emissions. However, the impact of negative shocks in NRR (NRR⁻) is less significant in the short run, with a coefficient of 0.0849 and a lower t-statistic, suggesting that the short-term effects of decreases in natural resource rents on CO₂ emissions are less pronounced. Positive shocks in financial inclusion (FI⁺) and negative shocks (FI⁻) have smaller and less significant impacts on CO₂ emissions in the short run, with coefficients of 0.0621 and 0.0646, respectively. Education (EDU⁺) and technological innovation (TI⁺) continue to show significant negative impacts on CO₂ emissions, with coefficients of -0.0732 and -0.0823, respectively, reinforcing the importance of these factors in reducing emissions. The negative shocks in education (EDU⁻) and technological innovation (TI⁻) also exhibit negative coefficients, indicating that even short-term reductions in these variables can improve environmental quality. However, the impacts are less significant compared to their long-term effects.

For energy sustainability, the long-run results reveal a significant negative impact of positive natural resource rent (NRR⁺) shocks on renewable energy consumption (REC), with a coefficient of -0.1692. Findings suggest that increases

in natural resource rents discourage the adoption of renewable energy. Negative shocks in NRR (NRR-) also negatively affect REC but with a smaller coefficient of -0.1174, indicating that reductions in natural resource rents also hinder renewable energy uptake, though to a lesser extent. Financial inclusion (FI⁺) positively impacts REC with a coefficient of 0.1764, indicating that increased access to financial services promotes renewable energy consumption. Negative shocks in financial inclusion (FI-) similarly exhibit a positive impact on REC, with a coefficient of 0.1709, suggesting that reductions in financial inclusion still support renewable energy adoption. Education (EDU⁺) and technological innovation (TI⁺) positively impact REC with coefficients of 0.1633 and 0.2968, respectively, highlighting the crucial role of education and innovation in promoting renewable energy. Negative shocks in education (EDU-) and technological innovation (TI-) also show positive coefficients, indicating that even reductions in these variables contribute to increased renewable energy consumption. However, the impacts are less pronounced compared to positive changes.

In the short-run results, positive shocks in natural resource rent (NRR⁺) continue to negatively impact REC, with a coefficient of -0.0906, indicating that short-term increases in natural resource rents discourage renewable energy consumption. However, the impact of negative shocks in NRR (NRR-) is less significant in the short run, with a coefficient of -0.0942, suggesting that short-term decreases in natural resource rents have a minor impact on renewable energy consumption. Positive shocks in financial inclusion (FI⁺) and negative shocks (FI-) have significant positive impacts on REC in the short run, with coefficients of 0.0675 and 0.0899, respectively, indicating that changes in financial inclusion strongly influence renewable energy adoption. Education (EDU⁺) and technological innovation (TI⁺) continue to positively impact REC in the short run, with coefficients of 0.0707 and 0.0462, respectively, reinforcing their importance in promoting renewable energy. The negative shocks in education (EDU-) and technological innovation (TI-) exhibit mixed impacts, with EDU- showing a negative coefficient of -0.0839, indicating that short-term reductions in education can hinder renewable energy consumption, while TI- remains positive but less significant, suggesting a complex interplay between innovation and renewable energy adoption in the short term.

The present study has enlarged the empirical estimation, especially for the long-run coefficients robustness investigation through MG, AMG, and CCEM. Referring to the results displayed in Table 9, the study confirmed a similar vein of linkage, unveiled in the earlier estimation in both the symmetric and asymmetric estimations. Thus, ascertain the robustness in empirical estimation and consistency in model construction.

5 Discussion of the findings

The study unveiled a positive statistical linkage between NRR and CO₂, exhibiting the contributory effect of NRR in degrading environmental sustainability through the emission of excessive CO₂. The finding is supported by existing literature such as [64, 73, 125–127, 129]. Empirical studies have shown a significant positive association between natural resource rents and ecological footprints in high- and low-income countries [70]. Natural resource rents improve the natural environment by reducing carbon emissions. However, the findings are inconsistent, as some studies indicate that natural resource rents are causing more carbon emissions in G7 countries [128]. The relationship between natural resource rents and carbon emissions is rooted in the economic phenomenon where revenues derived from natural resources significantly impact a country's economy. When these rents form a large part of a nation's wealth, there is a tendency to rely heavily on resource-intensive industries for economic growth, accelerating carbon emissions due to the energy-intensive nature of extracting, processing, and consuming these resources [128]. Extractive industries are responsible for half of the world's carbon emissions and more than 80% of biodiversity loss. The global economy has focused on improvements in labor productivity at the cost of material and energy productivity. This has led to a diminishing rate of return as resources become more expensive to extract and the environmental impacts become more significant [70]. The challenge lies in balancing economic development with environmental sustainability, particularly for resource-rich countries aiming to harness their natural wealth while mitigating the adverse effects on climate. This requires thorough investigation and the implementation of appropriate policy measures to achieve a harmonious equilibrium between the advantages of natural resource rents and the imperative of environmental preservation.

The relationship between the income generated by fossil fuel resources and the acceptance of renewable energy is complex. The study of [130] advocated that the existence of substantial natural resource revenues derived from fossil fuels might hinder the general acceptance of renewable energy, which occurs due to the potential for heightened dependence on traditional energy sources, thereby impeding the shift towards more environmentally friendly

Table 9 Results of robustness estimation: MG, AMG, and CSARDL

	Coeff	std. error	t-stat	Coeff	std. error	t-stat	Coeff	std. error	t-stat
Panel –A: Energy sustainability measured by REC									
NPR	– 0.0119*	0.0078	– 1.5256	– 0.0528***	0.0022	– 24.022	– 0.0421***	0.0085	–4.9529
EDU	0.0269***	0.009	2.9888	0.0155***	0.0062	2.5094	0.1218***	0.0053	22.9811
FI	0.0325***	0.0048	6.7708	0.1169***	0.006	19.4833	0.1285***	0.0031	41.4516
TI	0.0676***	0.0103	6.5631	0.015	0.0104	1.4423	0.1108***	0.0099	11.1919
c	2.4111***	0.2942	8.1954	3.9376***	0.9106	4.3241	3.8264***	0.2072	18.4671
CD test		0.0251			0.0312			0.0261	
Wooldridge test for autoco		0.4473			0.4118			0.7396	
Normality test		0.1028			0.9468			0.4262	
Remsey RESET test		0.9240			0.1785			0.4091	
Panel –B: Environmental sustainability measured by CO2									
NRR	0.0669***	0.0104	6.4326	0.134***	0.0065	20.6153	0.1257***	0.0025	50.276
EDU	– 0.0747***	0.0104	– 7.1826	– 0.0241***	0.0064	– 3.7656	– 0.0451***	0.0031	–14.5483
FI	0.0724***	0.0058	12.4827	0.1154***	0.0057	20.2456	0.1125***	0.0047	23.9361
TI	– 0.0928***	0.0047	– 19.7446	– 0.022***	0.0084	– 2.619	– 0.1817***	0.0062	–29.3064
C	4.2884***	0.8773	4.8881	1.5362***	0.7544	2.0363	1.1189	1.0522	1.0633
CD test		0.0302			0.0277			0.0261	
Wooldridge Test for auto		0.0249			0.0267			0.0278	
Normality test		0.0292			0.0269			0.0326	
Remsey RESET test		0.0317			0.0293			0.0221	

Note: the superscript of *** /**/* denote the level of significance at a 1%,5%, 10% respectively

options[131, 132]. Furthermore, redirecting these rents into renewable energy projects may promote the progress and implementation of more environmentally friendly energy sources [133].

An investigation has shown a direct relationship between the income generated from natural resources and the impact on the environment, as measured by ecological footprints, which indicates that nations with significant natural resource revenues often have greater ecological footprints, which may be ascribed to the energy-intensive procedures used in the extraction and refinement of these resources [4]. [75] has shown that oil rents, coal rents, forest rents, and mineral rents are linked to a rise in per capita CO₂ emissions. Curiously, there seems to be a negative relationship between gas rentals and CO₂ emissions per capita [74]. [134] carried out to assess the shift towards renewable energy in nations significantly dependent on oil and gas production within the context of renewable energy adoption, emphasizing the distinct difficulties encountered by these countries, considering their intricate position as both energy suppliers and buyers in the worldwide market [69]. To mitigate the adverse effects of significant revenues generated from natural resources on adopting renewable energy, it is crucial to implement regulations that encourage the transition to more sustainable energy sources. These strategies include providing financial assistance for renewable energy projects, giving tax breaks to enterprises that adopt renewable energy, and promoting public acceptance and community engagement in the growth of renewable energy [133]. Furthermore, using geospatial analytics may significantly improve the efficiency and efficacy of renewable energy projects while also considering the needs of other land uses [135].

A positive statistically significant linkage was disclosed between education and environmental quality; that is, the coefficients of EDU on Co₂ and ecological footprint exposed negatively associated. Study findings have postulated a contributory role of education in restoring environmental correction and ecological stability. The existing literature supports our findings, for instance, [38]; the findings indicate that education has a significant role in promoting environmental conservation and restoring ecological equilibrium. A positive and statistically significant correlation between education and environmental quality suggests that higher levels of education are linked to improved environmental outcomes. The coefficients of the variable "EDU" about "CO₂" and "ecological footprint" exhibited a negative association. This suggests that higher levels of education are linked to reduced CO₂ emissions and ecological

footprints. The discovery mentioned above is positive, as it implies that education possesses the potential to serve as a formidable instrument in advancing the cause of environmental sustainability.

The literature review serves to substantiate this particular finding further. Numerous studies have demonstrated a positive correlation between educational attainment and adopting pro-environmental attitudes and behaviors [136, 137]. Furthermore, it has been observed that there exists a positive correlation between institutional quality, frequently associated with levels of education and environmental quality. Moreover, a comprehensive investigation exploring the effects of education and unemployment on CO₂ emissions has revealed a significant correlation between higher levels of education and reduced CO₂ emissions. A recent study has investigated the interconnections between natural resources, renewable energy consumption, and environmental quality. The findings of this study indicate a positive correlation between CO₂ emissions and economic growth and energy consumption.

The findings of this study indicate that education has the potential to contribute significantly to the advancement of environmental sustainability. The augmentation of education levels can enhance the likelihood of individuals embracing pro-environmental attitudes and behaviors, thereby resulting in improved environmental outcomes [68]. Furthermore, it is worth noting that an increase in higher education levels has been found to correlate with enhanced institutional quality. This, in turn, can play a significant role in fostering improved environmental outcomes [67].

The coefficients of FI on environmental sustainability, which are proxied by CO₂ and EF, were positive and statistically significant in all three estimations. Moreover, the robustness assessment established a similar vine of connection. Our findings are in line with [138–140]. Study findings reveal an intricate relationship between financial inclusion and environmental degradation, encompassing short-term and long-term dynamics. Our findings are consistent with the prevailing theory that suggests a strong correlation between these two domains. The authors specifically assert the concept that a financial system that is easily accessible possesses both positive and negative consequences. On one hand, it provides a robust mechanism for mitigating risks, mobilizing resources efficiently, and ensuring effective corporate governance. Furthermore, it serves as a catalyst, driving industrial activities with the potential for enhanced economic prospects. Unfortunately, the current economic upswing frequently results in a simultaneous rise in environmental deterioration.

However, our findings diverge from an alternative theoretical viewpoint that suggests the potential of the financial system to promote environmental sustainability. Theoretically, a robust financial infrastructure should effectively support mitigating greenhouse gas (GHG) emissions. The proposed approach aims to address the issue by mitigating financial limitations and decreasing borrowing expenses for both individuals and businesses, which, in turn, would create incentives for investments in environmentally sustainable green technology. In contrast to the supposition above, our findings challenge this hypothesis, indicating that the association between financial development and environmental quality is characterized by a more intricate and potentially unfavorable nature. It is worth noting that our conclusions align with the empirical findings of [138] and Ju, Andriamahery [141]. The research conducted by the authors supports the notion that easily accessible financial systems might have the unintended consequence of worsening environmental degradation rather than improving it. The aforementioned parallel findings highlight the necessity of developing a comprehensive comprehension of the complex interplay between financial inclusion and environmental sustainability. This underscores the significance of implementing policy measures that effectively address the negative environmental consequences linked to financial development.

6 Conclusion, policy suggestion and future direction

6.1 Conclusion

The motivation for this study was driven by the need to understand the intricate relationships between natural resource rent, education, financial inclusion, and technological innovation in the context of environmental and energy sustainability. This research aimed to fill the knowledge gap by employing a robust analytical framework that included panel data analysis, cointegration tests, and the estimation of asymmetric coefficients across a diverse range of countries.

Key findings from our analysis provide significant insights into the interplay between socioeconomic factors and environmental outcomes:

First, the study found a direct correlation between natural resource revenue (NRR) and carbon dioxide (CO₂) emissions, underscoring the negative environmental impacts of exploiting natural resources and highlighting the urgent need for responsible resource management to mitigate ecological degradation caused by extractive industries.

Second, Our study revealed that higher levels of education are associated with lower CO₂ emissions and reduced ecological footprints. This finding emphasizes the critical role of investing in human capital to foster environmentally friendly behaviors and mindsets. Education is a powerful tool for promoting environmental literacy and empowering individuals to adopt sustainable practices.

Third, The research identified a concerning link between financial inclusion and environmental degradation. While financial inclusion can drive economic progress, our results indicate that unregulated financial inclusion can exacerbate environmental issues. This finding underscores the importance of aligning financial practices with sustainability objectives to balance economic growth with environmental stewardship.

Fourth, Technological advancements, particularly in green technologies, have been instrumental in reducing CO₂ emissions, highlighting the importance of fostering an environment that promotes innovation and encourages investment in research and development of clean technologies to accelerate the transition to a sustainable future.

6.2 Policy suggestions

Before discussing these policy proposals, it is crucial to recognize the urgent requirement for comprehensive action to tackle environmental degradation and promote sustainability. With climate change, biodiversity loss, and resource depletion becoming more pressing, policymakers must prioritize implementing effective strategies to reduce environmental impacts and protect the planet for future generations. The following policy suggestions provide practical and feasible actions to advance environmental conservation, encourage sustainable development, and stimulate green innovation. By incorporating these policies into broader environmental governance frameworks, policymakers can initiate significant changes toward a more resilient and equitable future.

First and foremost, allocating resources toward environmental education initiatives across different educational levels can effectively enhance knowledge and consciousness regarding sustainability matters and encourage responsible environmental behaviors. Individuals can better comprehend environmental issues and potential solutions by incorporating environmental education into school curriculums and community outreach programs, focusing on conservation, renewable energy, and sustainable practices. This approach cultivates a sense of environmental responsibility from a young age, empowering individuals to make informed choices that contribute to long-term environmental sustainability.

Secondly, it is essential to introduce regulations that incentivize financial institutions to invest in environmentally friendly projects and integrate environmental factors into their lending practices, which can be achieved by enforcing rules that mandate the disclosure of environmental risks, offering tax benefits for green investments, and establishing standards for green finance to guide investment decisions. By doing so, policymakers can encourage private capital allocation towards sustainable initiatives, aligning financial incentives with environmental objectives, accelerating the transition to a low-carbon economy, and promoting sustainable development.

Thirdly, providing financial support through subsidies, tax credits, and feed-in tariffs is crucial in encouraging renewable energy technologies and decreasing dependence on fossil fuels. Policymakers can effectively promote investment and implementation of clean energy infrastructure by offering specific incentives for solar, wind, and hydroelectric power projects. These incentives help make renewable energy more competitive than traditional energy sources, leading to innovation, creating green jobs, and reducing greenhouse gas emissions.

Fourthly, offering financial assistance through grants and funding is essential to support research and development in clean technologies, energy efficiency, and sustainable manufacturing processes. Policymakers can achieve this by creating grant programs that cater to universities, research institutions, and private companies. This approach will expedite the progress and implementation of innovative solutions for environmental problems. These grants encourage technology, spur economic growth, enhance competitiveness, and address pressing environmental issues like climate change and pollution.

Fifth, facilitating the transition to a circular economy model is essential for minimizing waste, maximizing resource efficiency, and promoting sustainable consumption and production patterns. This can be achieved by implementing policies incentivizing recycling, reusing, and remanufacturing, such as extended producer responsibility schemes and product stewardship programs. By optimizing the use of resources and minimizing environmental harm throughout the product lifecycle, circular economy initiatives create economic value, conserve natural resources, and mitigate environmental degradation.

Finally, supporting community-led conservation efforts that engage local stakeholders in sustainable land management and biodiversity conservation is paramount. Policymakers can empower communities by offering financial resources and technical assistance for community-based conservation projects. These programs promote sustainable living, safeguard biodiversity, and build resilience against environmental issues. By doing so, they foster a sense of ownership and stewardship among local communities.

6.3 Constraints and prospects for future research

Although this research is extensive, it is important to recognize certain limitations. Initially, the study focused on eight nations with abundant natural resources. However, this narrow scope may not comprehensively understand the various approaches to managing and sustaining natural resources worldwide. Subsequent investigations may consider enlarging the sample to include a more diverse array of nations, including different economic frameworks and environmental regulations. Furthermore, the research mostly relied on secondary data sources, which might potentially include inherent biases or mistakes. Future research endeavors might be enhanced by integrating primary data from surveys or case studies, yielding more intricate and detailed insights. Furthermore, the research analyzed the influence of technical innovation, but it did not distinguish between various categories of inventions or industries. Further investigation might examine the varying effects of technology breakthroughs on businesses and their particular contributions to sustainability. Finally, while the study's analytical methods are strong, they might benefit from including further sophisticated econometric tools to corroborate the results and gain more profound insights. Machine learning algorithms may forecast sustainability outcomes by analyzing intricate relationships among the factors under study.

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Data availability Data Availability Statement: The data used in the study can be found at <https://stats.oecd.org/> and <https://ourworldindata.org/research-and-development>, here mentioned that all the data are freely accessible.

Declarations

Informed consent Not applicable.

Competing interests The authors declare no competing interests.

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