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Escaping the carbon curse: the roles of technological innovation, green growth and green finance in resource-rich economies

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ABSTRACT

Resource-rich economies often face the carbon curse, where heavy reliance on natural resources leads to higher emissions and slower environmental progress. Policy tools such as technological innovation, green growth, and green finance are widely promoted to address these challenges. However, their effectiveness varies, and linear models may overlook important threshold effects, where these tools only work after reaching critical levels of development or investment. This study interrogates the existing evidence and offers some masterpiece pathways for escaping the carbon curse of natural resources. Using a dataset from 2000–2023 and Hansen (1999) threshold model, the findings are as follows: The linear model shows that technological innovation and green finance are positively associated with carbon emissions and energy intensity. Green growth appears more beneficial, showing negative effects on emissions across models. However, threshold analysis reveals that all three policy instruments – technological innovation, green growth, and green finance – only yield significant environmental benefits above specific critical levels. Below these thresholds, their impact is either negligible or harmful, reinforcing the idea that policy maturity and scale are essential. These findings highlight the need for resource-rich countries to exceed key policy and investment thresholds to achieve effective decarbonization. A targeted approach to scaling innovation, strengthening green growth frameworks, and strategically allocating green finance is crucial to escaping the environmental traps of resource dependence.

KEYWORDS

Carbon curse; green growth; green finance; technological innovation threshold regression; resource-rich economies

1. Introduction

Natural resource abundance, especially minerals and fossil fuels, has traditionally catalyzed economic advancements in resource-endowed nations, offering a comparative efficiency that spurs structural transformation and socioeconomic advancement (Nwani et al. 2025). However, this resource-driven growth model has faced intensified scrutiny for its ecological impacts, particularly the uptick in carbon footprint resulting from the resource exploitation, combustion and processing (Okere, Dimnwobi, and Fasanya 2024a,b). This duality of resource endowments boosting economic progress while aggravating ecological harm is known as the Carbon Curse of Natural Resources (CCNR) (Khan, Rahman, et al. 2024; Murshed 2024). Consequently, resource assets represent both an economic blessing and ecological burden. Given the escalating climate demands and global sustainability pledges, especially Sustainable Development Goal (SDG) 13 on climate action, mitigating the CCNR by minimizing the carbon footprint linked to resource abundance has emerged as a pressing policy agenda (Murshed and Rahman 2025). However, it is not desirable to completely abandon resource utilization in light of the central role of hydrocarbons and minerals in infrastructure, energy systems and innovative sustainable technologies (Khan, Rahman, et al. 2024; Murshed 2024). The critical challenge involves the transition from the resource-based growth into an ecological sustainable model.

Two vital theories notably ecological modernization theory and transition theory offers detailed theoretical insights for this transformation. While the former contends that economic advancements and ecological quality can align through technological innovation, market instruments and institutional reform,

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the latter underlines the criticality of systemic changes within socio-technical configurations such as production systems, finance and energy to facilitate the transitions to low-carbon economy (Hammami et al. 2025; Samour et al. 2024). In light of these theoretical lens, three policy instruments are identified as critical to de-cursing the CCNR namely green finance, technological innovation and green finance. For instance, green finance harnesses capital toward ecological sustainable initiatives, disincentivizing investment in carbon-heavy sectors (Zaka et al. 2025). Technological innovation encompassing clean energy technologies, sustainable production systems and carbon abatement technologies can facilitate low-carbon economic development (Siripi, Kuuwill, and Tamakloe 2024). Green growth redefines development initiatives around circular economy frameworks, energy efficiency and sustained ecological stability Dhayal et al. (2025).

This study estimates the influence of these levers notably green growth, green finance and technological innovation on alleviating the CCNR in resource-endowed economies. These nations, marked by high natural resource income, experience substantial economic and ecological vulnerabilities. According to World Bank (2024) reports, the ratio of resource rent to GDP in these nations considerable surpasses the world average of 3%. For example, Mongolia (33.1%), Azerbaijan (29.9%), Kazakhstan (26.8%), Algeria (22.6%), Uzbekistan (20.5%), Chile (16.9%), Peru (12.7%) and Kyrgyz Republic (11.5%) exemplify nations where resource wealth drives nation income but also coincides with rising carbon emissions driven by intensive fossil energy use and resource extraction activities. In spite of these constraints, most of these nations have begun implementing ecological and policy reforms. For instance, Chile has made significant progress in green finance by issuing sovereign green bonds and advancing sustainable finance models (Madeira and Pérez 2023). Kazakhstan has embraced green energy benchmarks and decarbonization strategies (Satubaldina 2025). Azerbaijan and Mongolia have commenced exploring sustainable mining technologies and innovation hubs (Destek et al. 2024). The foregoing emphasize that policy momentum is emerging as a key development priority in these economies.

Despite the increasing scholarship on CCNR, empirical evaluations on resource-endowed nations are limited. Yet, these nations, in the light of their intense reliance on conventional energy sources and resource extraction, are essential to comprehending and tackling the CCNR. This research bridges the gap by concentrating solely on resource-rich economies where carbon footprint associated with resource exploitation and utilization is strikingly pronounced. Second, previous studies have predominantly utilized sole proxy to capture carbon curse, commonly carbon intensity and carbon emissions, this study employs a dual-indicator strategy, utilizing both carbon intensity and energy intensity. This facilitates a multidimensional evaluation of the ecological pressure arising from resource utilization, documenting both carbon concentration per unit of output and the energy inefficiency. Third, although green growth, technological innovation and green finance have been widely acknowledged as strategic instruments for ecological quality, previous studies have failed to methodically estimate their threshold impacts in decoupling the carbon curse within resource-endowed economies. This research responds to this shortcoming in the extant literature by evaluating whether the variables can act as de-cursing" tools, establishing the points at which they begin to considerably alleviate the CCNR. Fourth, unlike past studies that have largely utilized conventional estimation approaches like Augmented Mean Group (AMG), Generalized Method of Moments (GMM) among others, this research applies the Hansen (1999) threshold regression model. This innovative methodology enables the detection of critical threshold levels of green growth, technological innovation and green finance that should be reached for their ecological benefits to manifest. To our research knowledge, this study represents the first attempt to estimate such nonlinear impact in the CCNR literature.

In the light of the foregoing motivations, this study expands the literature in multiple key aspects. First, it broadens the empirical frontier of CCNR research by focusing on nations most exposed to its impacts. Second, we introduced a more comprehensive measurement model by merging carbon and intensity metrics to uncover the entire range of environmental burden. Third, the study assesses the overlooked role of sustainability factors as threshold-based de-cursing mechanisms. Fourth and most importantly, it provides actionable threshold values that decisionmakers can employ to effectively foster innovation, deploy sustainable finance and advance eco-friendly growth. The outcome of this study is very pertinent to public policy, particularly for assisting resource-rich nations synchronize their development agenda with the United Nations 2030 SDG. For example, the research provides guidance toward attaining SDG 7

(Affordable and Sustainable Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action) by underscoring how much green innovation and investment are "enough" to unlink economic expansion from emissions

The reminder of the study has four sections. The next section discusses the relevant literature while Section 3 provides the data and methods applied in the study. Section 4 contains the empirical results while Section 5 concludes the study

2. Literature review

2.1. Theoretical background

The carbon curse concept originates from the foundational principles of the resource curse. Resource endowments are traditionally regarded as drivers of economic advancements. However, in the last five decades, numerous resource-scarce nations have surpassed their resource-rich peers by adopting innovation, diversification and governance reforms. Conversely, most resource-endowed economies have recorded stagnant growth, hence fueling concerns about the validity of the traditional growth paradigms (Aladejare and Dimnwobi 2025). Consequently, Auty (1993) formally proposed the "resource curse" to explain the paradox whereby resource assets impair instead of catalyzing sustained development outcomes. Some of the primary enablers of resource curse include rent-seeking behavior, poor governance frameworks and structural path dependence (Okere, Dimnwobi, and Fasanya 2025a,b). In recent times, scholars have expanded this analysis to the carbon curse, which documents how the continued reliance on natural resource wealth may obstruct carbon efficiency and obstruct the transitions to green economy. Economies burdened by the carbon curse frequently struggle to decouple economic progress from ecological degradation, highlighting the criticality of decoupling theory (Khan, Rahman, et al. 2024; Murshed 2024). This reliance on fossil-fuel-driven growth patterns indicates not just economic inflexibility but also technological and institutional inertia. The Environmental Kuznets Curve (EKC) proposition offers only a limited insight, indicating that ecological pollution increases with income level at the initial stages of development but ultimately reduces as the economies expand and began to utilize sustainable technologies (S. K. Dimnwobi, Okere, et al. 2023). However, resource-endowed nations are usually unable to attain this turning point owing to persistent dependency on fossil fuel and limited diversification (S. K. Dimnwobi, Okere, et al. 2023). Conversely, the Ecological Modernization Theory (EMT) provides a more optimistic outlook, contending that institutional strengthening, policy reform and technological advancements, economies can adequately harmonize environmental and economic objectives (Onuoha et al. 2023a,b). In this context, green growth, technological innovation and green finance have become critical levers for mitigating the impact of carbon curse. Green finance directs capital toward clean technologies and low-carbon infrastructure and promotes the required structural transformation for sustainable development. Similarly, green growth strategies incorporate ecological sustainability into development planning, thereby providing an escape from carbon-intensive growth. The role of technological innovation is also very vital as it promotes green energy utilization, enhances energy efficiency and lowers industrial emissions. Collectively, these mechanisms agree with EMT and support the Porter Hypothesis, which argues that effective ecological policies can spur innovation and stimulate competitiveness

2.2. Natural resources and carbon emissions

Previous studies have assessed the validity of the CCNR by assessing how resource abundance influences carbon emissions, with some studies supporting the CCNR hypothesis, while others provided evidence refuting the hypothesis. CCNR is valid when a surge in resource utilization results in the expansion of emission level and it is invalid or disproved when emissions level is considerably decreased by resource abundance. Both strands of literature are discussed in this section beginning with those that validate the CCNR hypothesis

These studies underline that resource wealth does not protect the environment. For instance, Hossain et al. (2022) report that resource wealth expands India's carbon emissions level. Likewise, Danish and Hassan (2023) confirm in Pakistan that natural capital aggravates ecological damage by increasing carbon emissions in the long term. Raihan et al. (2024) find that resource abundance intensifies emission level in Bangladesh. Fan et al. (2022) assessed the influence of resource dependence on China's carbon emission efficiency and revealed that resource reliance impedes low-carbon transition. The outcome of this study confirms the existence of carbon emission efficiency curse in China. Shen et al. (2021) argue that resource reliance escalates emission levels in China, showing that resource assets damage the ecosystem. The carbon curse of resource abundance is also supported in Cambodia (Qamruzzaman 2024), demonstrating that resource abundance results in substantial ecological decline. In a broader Asian literature, Y. Li et al. (2022) and Nguyen et al. (2023) establish that the resource utilization triggers the destruction of the ecosystem, thereby endorsing the CCNR.

Murshed (2024) observes that while resource dependency aggravates the carbon curse trap in Asian economies, reducing external tensions can substantially reduce the carbon curse of resource abundance. This also relates to the conclusion of another study in Asia (Murshed and Rahman 2025). The authors document that natural resources stimulate carbon emissions but this can be considerably mitigated by reducing geopolitical dispute in the region. Put differently, these authors indicate that the joint impact of resource endowments and conflict resolution can mitigate the carbon curse in these economies. Likewise, Khan, Rahman, et al. (2024) reports that resource wealth triggers carbon emission trap in resource-endowed nations but this CCNR is mitigated by Fintech development. Put differently, the joint effect of resource wealth and Fintech development lessens the CCNR and improves the environment.

The foregoing is contingent on aggregated resource assets, other studies have estimated the effect of natural resource on emission using disaggregated resource types. For instance, Ouédraogo et al. (2022) and Achuo, Miamo, and Kouhomou (2024) validated the CCNR in African economies by discovering that the extraction of mineral resources substantially increases carbon emission. Nwani et al. (2021) confirm the carbon curse of oil endowment in Algeria, indicating that unsustainable resource utilization substantially results in long-term ecological damage. Likewise, W. Wang et al. (2023) reports that resource dependence (oil and gas rents) aggravates emission level in China. In a recent study of China, Lee, Du, and Wang (2024) disclose that mineral resource abundance instead of mitigating emission aggravates ecological outcomes in China, aligning with the carbon curse hypothesis

Conversely, other scholars have rejected the CCNR hypothesis by highlighting that resource abundance enhances ecological quality. For instance, N. Amin et al. (2023), X. Li and Yang (2023), Shah et al. (2023) and Voumik, Mimi, and Raihan (2023) disproved the CCNR hypothesis in South Asia by discovering that natural resources empower ecological preservation. L. Zhang et al. (2021) reinforced this conclusion in Pakistan by showing that resource endowments promote ecological integrity. Similarly, another evidence from five European nations (Balsalobre-Lorente et al. 2018) refutes the CCNR propositions, highlighting that resource abundance reduces emission level thereby enhancing environmental sustainability. The outcome of Xiaoman et al. (2021) in MENA economies is also not different as the authors discovered that natural wealth improves environmental performance in MENA economies.

2.3. Technological innovation and carbon emissions

The endogenous growth theory states that technological innovation is a critical driver in tackling environmental pollution. It is usually theorized that technological advancements result in greener production methods and enhanced energy efficiency which ultimately mitigates carbon emissions. However, available evidence on this nexus is inconclusive. While some scholars endorse the position that technological advancements lessen carbon emissions by facilitating green innovation and practices, others dispute this evidence, arguing that technology can also expand emission levels through a rise in energy use and production scale effects. This section reports this varied outcome beginning with those documenting the enhancing influence of technological innovation on environmental quality. For instance, Z. Khan et al. (2020) reports that technological innovation improves the ecosystem by reducing carbon emission in G7 economies. F. Li and Yan (2024) also discovered that technological innovation results in the reduction of carbon emissions in selected economies within the Shanghai Cooperation Organization. Hashmi and Alam (2019), Obobisa (2024) and Hassan, Khan, and Khan (2025) made similar observations in OECD economies. This conclusion is supported by Ali et al. (2023), Chen et al. (2023), Ma, Murshed, and Khan (2021), Habiba, Xinbang, and Anwar (2022) and X. Wang et al. (2025) in China, carbon-intensive economies, Saudi

Arabia, Bangladesh and GCC region. In African context, Obobisa, Chen, and Mensah (2022) argue that carbon emission is mitigated by technological advancements, indicating that technological innovations protect the environment. Switching to country-level African studies, Ibrahiem (2020) reveal that technological innovation stimulates ecological excellence by reducing carbon emissions. These studies showed that technological innovations are linked with reduction in carbon emissions. Conversely, there are other scholars that report that technological innovation undermines environmental sustainability by increasing emission level. Rahman and Alam (2022) documents that technological innovation expands emission level in Asian economies. Analogously, Villanthenkodath and Mahalik (2022) demonstrate that technological advancements trigger India's ecological damage. This conclusion is also supported by evidence from other contexts like Portugal (Adebayo et al. 2022); Japan (Adebayo and Kirikkaleli 2021) and Ghana (Siripi, Kuuwill, and Tamakloe 2024)

2.4. Green growth and carbon emissions

Green growth is increasingly viewed as a vital strategy for attaining economic advancements while protecting the ecosystem. This concept stresses decoupling economic progress from ecological degradation through strategies that advance green energy, resource efficiency and green development. Extant studies widely affirm that sustainable growth promotes environmental outcomes, especially by decreasing carbon emissions and boosting ecological efficiency. For instance, Hao et al. (2021) explore the influence of sustainable growth on carbon emission in G7 economies, reporting that green growth improves the environment. In the context of emerging economies, Dhayal et al. (2025) concludes that green growth accelerates environmental sustainability by reducing carbon emission in emerging economies. Dogan, Hodžić, and Šikić (2022), employing data from 25 economies establish that environmental preservation is substantially enhanced by green growth. This indicates that green growth results in a reduction of carbon emissions. Chien et al. (2021) and Yang, Shahzadi, and Hussain (2021) analyzed the environmental impact of green growth in USA and report that green growth promotes environmental excellence by mitigating carbon emissions. In a similar study of China, Dong et al. (2022), J. Zhao et al. (2022) and A. Amin et al. (2024) argue that green development is critical in reducing carbon emission, hence indicating that green growth is a key pathway to transitioning to low-carbon economy. This outcome is reinforced by a similar evaluation in Pakistan (Lin and Ullah 2023) indicating that sustainable growth mitigates ecological damage by substantially lessening carbon emissions. This is further confirmed in a broader Asian context (Saleem, Khan, and Mahdavian 2022) indicating that green growth is pro-environment

2.5. Green finance and carbon emissions

Green finance has emerged as an effective tool for tackling climate change by channeling funds toward ecological sustainable initiatives. Previous studies predominantly documented that green finance improves environmental outcomes. For instance, J. Wang et al. (2023) utilizing data from China reports that green finance is essential in improving the environment. Likewise, in China, Wu, Liu, and Cai (2024) reinforce the enhancing influence of green finance on environmental quality. This is also supported by other evidences from China (Chen and Chen 2020; Huang et al. 2024; X. Su, Qiao, and Xu 2024; Y. Wang, Cui, and Zhou 2024), highlighting that green finance is pro-environment. Focusing on 21 economies, Hunjra et al. (2024) documents that expansion in green finance results in improved environmental outcomes by encouraging low-carbon investments. N. Amin et al. (2025) demonstrates that green finance lowers carbon emissions by boosting environmentally sustainable projects in BRICS economies. The same conclusion is established in OECD nations (Umar and Safi 2023; T. Wang et al. 2023). In a recent evaluation of emerging economies, Zaka et al. (2025) affirm that the environment is significantly shaped by green finance. Collectively, these studies confirm that green finance is pro-environment as it drives the transition to a low-carbon economy.

2.6. Empirical gaps

The review of extant studies on the CCNR documents numerous vital limitations that this research addressed. First, existing literature have predominantly concentrated on China or utilized cross-country or global samples. While insightful, such strategies usually obscure the context-specific dynamics of resource-endowed nations that is considerably more at risk of carbon curse. Consequently, the unique economic and ecological challenges experienced in these economies remain neglected by past studies. Second, current studies usually depend on a sole ecological metric, most commonly carbon intensity or carbon emissions as a surrogate for carbon curse. This limited approach is unable to document the comprehensive scope of ecological burden resulting from resource extraction. The utilization of both carbon intensity and energy intensity in this study provides a thorough evaluation. Third, while green growth, technological innovation and green finance have been examined individually with respect to ecological outcomes, no study has jointly estimated their threshold impacts in alleviating the carbon curse within resource-endowed nations. This highlights a notable research void, especially given the capacity of these variables to serve as nonlinear "de-cursing" pathways. Fourth, the conventional analytical approaches have been widely employed in current studies and these techniques usually assume linearity and are unsuitable for unearthing the threshold dynamics critical for effective policy design. The utilization of Hansen's (1999) threshold regression model in this research permits the determination of minimum threshold levels of green growth, technological innovation and green finance that can considerably neutralize the CCNR. The preceding empirical shortcomings underscore the criticality of a multidimensional, nonlinear and targeted approach, one provided in this study by exclusively concentrating on resource-rich nations and applying advanced threshold modeling.

3. Methodology

3.1. Theoretical framework

The IPAT models, originally formulated by Ehrlich and Holdren (1971) and later refined into STIRPAT by (Dietz and Rosa 1994; York, Rosa, and Dietz 2003), serve as foundational analytical tools for quantifying the environmental consequences (impacts) of human activity. These models break down environmental impact into key drivers such as population, affluence, and technology, allowing for a structured analysis of how societies contribute to environmental degradation. They are frequently situated within the broader discourse of the Environmental Kuznets Curve (EKC) hypothesis, which suggests a non-linear, inverted U-shaped trajectory between environmental degradation and economic development (Abbas et al. 2025). Beyond the EKC framework, their integration with the Resource Curse Hypothesis [1]offers a more detailed lens through which to interrogate the complex interplay among economic growth, natural resource endowments, and environmental outcomes, enabling a richer, multidimensional understanding of sustainability dynamics.

In this context, the incorporation of technological innovation, green growth, and green finance STIRPAT framework will act as transformative forces that can disrupt the typical trajectory predicted by the resource curse. For instance, technological innovation improves production efficiency and enables cleaner industrial processes (Sinha, Singh, and Soni 2017). Green growth encourages economic expansion that is environmentally sustainable (Razelan et al. 2024), while green finance mobilizes capital toward renewable energy, sustainable infrastructure, and low-carbon technologies (X. Liu et al. 2023).

Accordingly, the STIRPAT model – an analytical extension of the IPAT framework designed to empirically assess the determinants of environmental impact – is formally represented by the following equation:

$$I_t = \varphi P_t^{\alpha} A_t^{\beta} T_t^{\delta} \tag{1}$$

Equation (1) captures a functional relationship in which environmental impact I_t is determined by three core factors – population P_t, affluence A_t, and technology T_t—each raised to an exponent and scaled by the elasticity parameters α, β, δ, respectively. These parameters quantify the percentage change in I_t associated with a 1% change in each explanatory variable. To facilitate empirical estimation and address the primary objectives of this study, Equation (1) is reformulated to integrate the Environmental Kuznets Curve (EKC)

[1]The Resource Curse Hypothesis suggests that countries rich in natural resources tend to experience slower economic growth compared to resource-poor economies due to weak institutions, overreliance on extractive industries, and environmental mismanagement (Sachs and Warner 2001).

framework and to investigate the carbon curse hypothesis. Building on the extant studies such as Murshed and Rahman (2025) Nwani et al. (2021), this modeling is achieved by incorporating carbon emissions, energy intensity, and carbon intensity into the model specification, as expressed below:

$$lnCO2_{i,t} = \theta_0 + \theta_1 lnP_{i,t} + \theta_2 lnGDP_{it} + \theta_3 lnGDPsq_{it} + \theta_4 lnZ_{i,t} + \varepsilon_{i,t} \tag{2}$$

$$lnEI_{i,t} = \theta_0 + \theta_1 lnP_{i,t} + \theta_2 lnGDP_{it} + \theta_3 lnGDPsq_{it} + \theta_4 lnNR_{i,t} + \theta_5 lnZ_{i,t} + \varepsilon_{i,t} \tag{3}$$

$$lnCI_{i,t} = \theta_0 + \theta_1 lnP_{i,t} + \theta_2 lnGDP_{it} + \theta_3 lnGDPsq_{it} + \theta_4 lnNR_{i,t} + \theta_5 lnZ_{i,t} + \varepsilon_{i,t} \tag{4}$$

Where, dependent Variable: $lnCO2_{i,t}$ = Log of carbon emission, $lnEI_{i,t}$ = log of Energy intensity, $lnCI_{i,t}$ – long carbon intensity for country/region i at time t. Independent Variables: $lnP_{i,t}$ = Log of population, which measures Population, total. $lnGDP_{it}$ = Log of gross domestic product (GDP), capturing the relationship between economic activity and its environmental impact. $lnGDPsq_{it}$ = Log of squared GDP, allowing for a nonlinear relationship (e.g., an inverted U-shape, as predicted by the EKC hypothesis). $lnNR_{i,t}$ = Log of natural resource rents (NR). $lnZ_{i,t}$ = Log of row vector, capturing role of technological innovation, green growth, and green finance. Error Term: $\varepsilon_{i,t}$ = Error term capturing unobserved factors affecting carbon emission, Coefficients: θ_0 = Intercept, $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ = regression coefficients, indicating the elasticity (percentage change in energy consumption resulting from a 1% change in each independent variable). To account for the EKC can be valid if $\theta_2 > 0$ and $\theta_3 < 0$.

3.2. Techniques

3.2.1. Threshold regression method and model settings: Hansen (1999) threshold

The second (core) objective of this study is to explore the possible links of escaping the carbon curse of natural resources through the lens of technological innovation, green growth, and green finance in the resource-rich countries. To address this, it is crucial to identify thresholds for technological innovation, green growth, and green finance that balance overreliance on natural resources with environmental sustainability. To achieve this, we employ Hansen (1999) threshold regression[2] to pinpoint the levels where these factors can simultaneously support robust environmental quality. This approach offers a pathway to ensuring a sustainable future.

$$Y_{it} = \beta_1 X_{it} I|q_{it} \leq \gamma| + \beta_2 X_{it} I|q_{it} > \gamma| + \mu_{it} \tag{5}$$

Dependent Variable: Y_{it} = The outcome of interest for unit i at time t (e.g., Log of carbon emission, log of Energy intensity, long carbon intensity for country/region i at time t). Independent Variables: X_{it} = The explanatory variable influencing Y_{it}. β_1 and β_2 = Coefficients measuring the effect of X_{it} before and after the threshold level $\gamma . q_{it}$ = The threshold variable, determining which regime applies. γ = The threshold value (technological innovation, green growth, and green finance), where the relationship between $X_{it}$and Y_{it}changes. Indicator Functions: $I|q_{it} \leq \gamma|$ = Equals 1 if $q_{it}$is less than or equal to γ (first regime) and 0 otherwise. $I|q_{it} \leq \gamma|$ = Equals 1 if $q_{it}$is greater than γ (second regime) and 0 otherwise. Error Term: μ_{it} = The stochastic error, capturing unobserved influences.

3.3. Sample selection

The dataset comprises eight resource-rich economies[3]—countries where natural resource rents exceed 10% of GDP. The sample is limited to eight economies due to limited data on technological innovation and green finance. The study covers the period from 2000 to 2023. Detailed explanations of the data are highlighted in Table 1.

[2]Hansen's (1999) threshold regression is a technique employed to ascertain a point (threshold) at which the connection between variables alters. This technique enables the identification of several regimes within the data, illustrating varying impacts of an independent variable on a dependent variable based on whether the threshold variable exceeds or falls below a specified value.

[3]Algeria, Azerbaijan, Chile, Kazakhstan, Kyrgyz Republic, Mongolia, Peru, Uzbekistan.

Table 1. Data description and sources.

Variables	Measurement	Source
Natural resources	Total natural resources rents (% of GDP)	World Bank
Technological innovation	Patents applications per million	Our World in Data
Green finance	International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems (millions of constant 2021 United States dollars)	Our World in Data
Green growth	Adjusted net savings, including particulate emission damage (% of GNI)	World Bank
Carbon emission	Annual CO2 emissions	Our World in Data
Economic growth	GDP per capita (constant 2015 US$)	World Bank
Population	Population, total	World Bank
Energy intensity	Energy intensity level of primary energy (MJ/$2017 PPP GDP)	World Bank
Carbon intensity	Carbon intensity of GDP (kg CO2e per 2021 PPP $ of GDP)	World Bank

Sources: Authors compilations. NR=Natural resources, TI=Technological innovation, GF=Green finance, GG=Green growth, Co2=Carbon emission, GDP=Economic growth, POP=Population, EI=Energy intensity, CI=Carbon intensity.

4. Results and discussions

4.1. Descriptive statistics

The correlation heatmap in Figure 1 provides a visual summary of the linear relationships between carbon emissions (CO_2) and various economic and environmental indicators. There are no strong linear associations and non-normality as seen in Appendix 1 between CO_2 emissions, energy intensity, carbon intensity and the other variables in the dataset. Notably, CO_2 shows slightly negative but weak correlations with carbon intensity (−0.13), green growth (−0.12), and GDP (−0.06), indicating that increases in these variables are marginally associated with reductions in carbon emissions. Other variables such as energy intensity show negligible negative correlations with all three policy indicators – technological innovation (−0.03), green finance (−0.02), and green growth (−0.03). carbon intensity is also weakly and negatively correlated with technological innovation (−0.06) and green growth (−0.05), while it shows no relationship at all with green finance (0.00). These patterns imply that technological advancement and progress in green growth may contribute slightly to lowering carbon emissions per unit of output, but the effects are minimal. In all, the data reveals a general lack of strong linear relationships among the variables. This could be interpreted from two angles: (i) It may suggest that carbon curse originating resource extractions are likely influenced by a broader set of factors not captured by these indicators alone. (ii.) It may imply the need for more complex, possibly nonlinear and empirical analyses to understand the underlying dynamics.

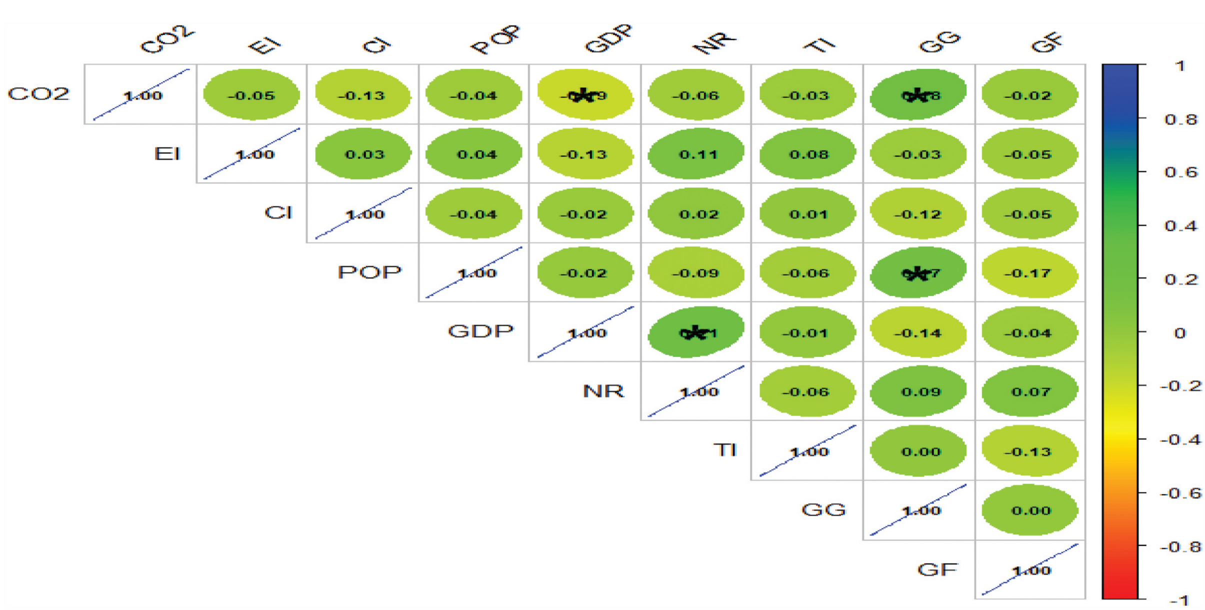


Figure 1. Correlation heatmap.

Figure 2 presents the spatiotemporal distribution of natural resource rents across countries for the years 2000 and 2023 based on data from the World Development Indicators. The figure captures how the reliance on and economic value derived from natural resources – such as oil, gas, minerals, coal, and forests – has evolved over a 12-year period. For instance, in 2010, high natural resource rents were concentrated in specific regions, notably in parts of Africa, some South American and Central Asian countries. These patterns reflect economies heavily reliant on natural resource extraction as a major source of income leading to carbon curse. By 2022, the distribution had shifted in several regions. Some countries appear to have reduced their dependence on natural resources, possibly due to emerging technological innovation, green growth, and green finance. In contrast, other countries show an increase in resource rents, suggesting heightened extraction activity.

To explore the potential for nonlinear and empirical analyses in understanding the underlying dynamics that may give rise to the carbon curse in the study region, we begin by employing a range of econometric techniques, as outlined in Figure 3.

4.2. Preliminary estaimation

The outcomes of the CD test (Table 2) provide strong evidence of cross-sectional dependency among most of the variables under investigation. This indicates substantial error overlap across the countries in the sample, particularly for variables. On this basis, the null hypothesis of cross-sectional independence is

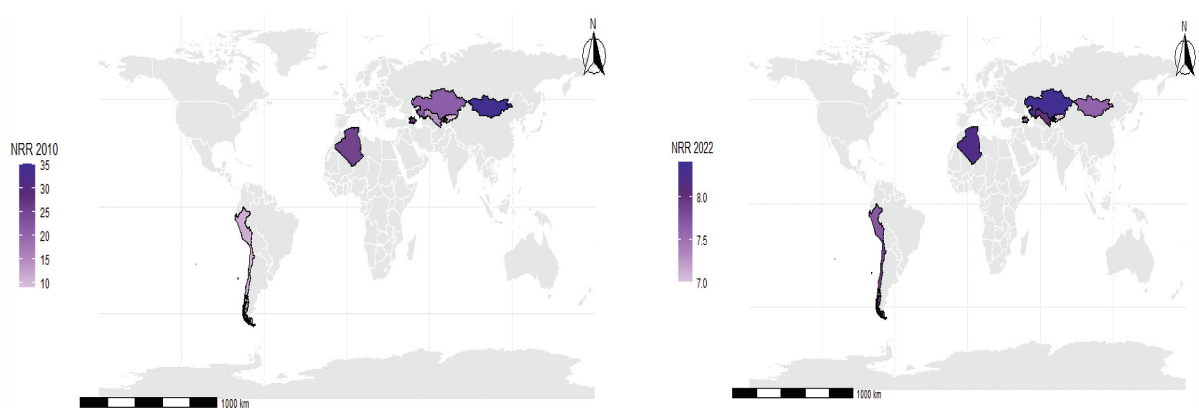


Figure 2. Spatiotemporal distribution of natural resource rents for 2000 and 2023 respectively. Data source: World Development Indicators.

Figure 3. Econometric protocols.

Table 2. CSD.

Variables	CD-test	p-value	average joint T	mean ρ	mean abs(ρ)
CO2	12.831***	0.000	24	0.49	0.78
CI	5.783***	0.000	24	0.22	0.56
EI	8.621***	0.000	24	0.33	0.71
POP	25.719***	0.000	24	0.99	0.99
GDP	24.616***	0.000	24	0.95	0.95
NR	14.559***	0.000	24	0.56	0.59
TI	10.343***	0.002	24	0.01	0.36
GG	9.143***	0.000	24	0.35	0.37
GF	11.658***	0.000	24	0.03	0.31

*** if $p < 0.01$, ** if $p < 0.05$, * if $p < 0.1$.

Table 3. Panel unit root.

	IPS		CADF	
Variables	I(0)	I(1)	I(0)	I(1)
CO2	0.704	−7.223***	−1.205	−4.813***
CI	−2.033	−6.788***	0.163	−4.845***
EI	−0.067	−6.362***	0.462	−4.922***
POP	12.201	0.050*	−1.416	0.046**
GDP	−2.3449**	−4.869***	−1.594	−2.755***
NR	1.462	−6.015***	1.805	−3.397***
TI	0.279	−6.643***	−1.327	−4.467***
GG	1.3453	−6.610***	0.768	−5.128***
GF	−3.516***	−8.050***	−3.260	−8.385***
GDPSQ	−1.918*	−4.990***	−1.576	−2.697***
NRTI	1.256	−5.874***	0.424	−4.177***
NRGG	1.218	−4.860***	1.920	−2.063***
NRGF	1.157	−5.951***	0.205	−5.191***

*** if $p < 0.01$, ** if $p < 0.05$, * if $p < 0.1$.

decisively rejected for these variables. The presence of such dependency validates the application of second-generation panel econometric techniques that explicitly account for cross-sectional dependence, thereby ensuring more robust and reliable estimation.

Two second-generation panel unit-root tests (IPS and CADF) in Table 3 and an error correction-based panel cointegration test (Westerlund ECM), and a slope heterogeneity diagnostic (Pesaran and Yamagata 2008) in Table 4 were employed, guided by the results of the cross-sectional dependency test. The panel unit-root tests indicate that most of the variables are non-stationary at level but become stationary after first differencing, suggesting that they are integrated of order one, I (1). While a few variables such as green finance (GF) and GDP show signs of level stationarity under IPS, the majority are confirmed as differenced stationary by both IPS and CADF methods. In the lower part of Table 4, the Westerlund cointegration test results strongly reject the null hypothesis of no long-run cointegration across all model specifications. This confirms that the variables converge toward a long-run equilibrium relationship. Additionally, multi-collinearity was ruled out, as all models reported low VIF values, well below the conventional threshold.

Table 4. Panel cointegration and slope heterogeneity test.

	Westerlund ECM-Cointegration Test								
	Model								
Statistic	1	2	3	4	5	6	7	8	9
Gt	−3.824***	−3.439***	−3.375***	−2.995***	−3.247***	−2.651***	−3.512***	−3.36***	−3.037***
Ga	−5.831***	−5.896***	−4.815***	−5.339***	−6.542***	−7.389***	−8.058***	−6.316***	−5.764***
Pt	−7.29***	−6.926***	−6.258***	−8.452***	−8.361***	−6.551***	−9.043***	−7.31***	−6.094***
Pa	−3.233***	−5.113***	−3.581***	−4.675***	−5.991***	−5.787***	−8.802***	−4.502***	−5.373***
Test for multicollinearity									
VIF	1.37	1.29	1.16	1.32	1.25	1.15	1.32	1.25	1.15
Testing for slope heterogeneity Pesaran and Yamagata (2008).									
Delta	12.745***	12.191***	13.072***	5.801***	6.017***	5.884***	7.908***	7.934***	7.814***
Adj	14.717***	14.077***	15.094***	6.892***	7.15***	6.992***	9.396***	9.427***	9.284***

Results for H0: no cointegration, H0: slope coefficients are homogeneous. *** if $p < 0.01$, ** if $p < 0.05$, * if $p < 0.1$.

Also, the slope heterogeneity test indicates significant heterogeneity in slope coefficients across countries. Taken together, these diagnostic results support the use of advanced panel estimation techniques that can account for both long-run relationships and heterogeneous cross-sectional dynamics.

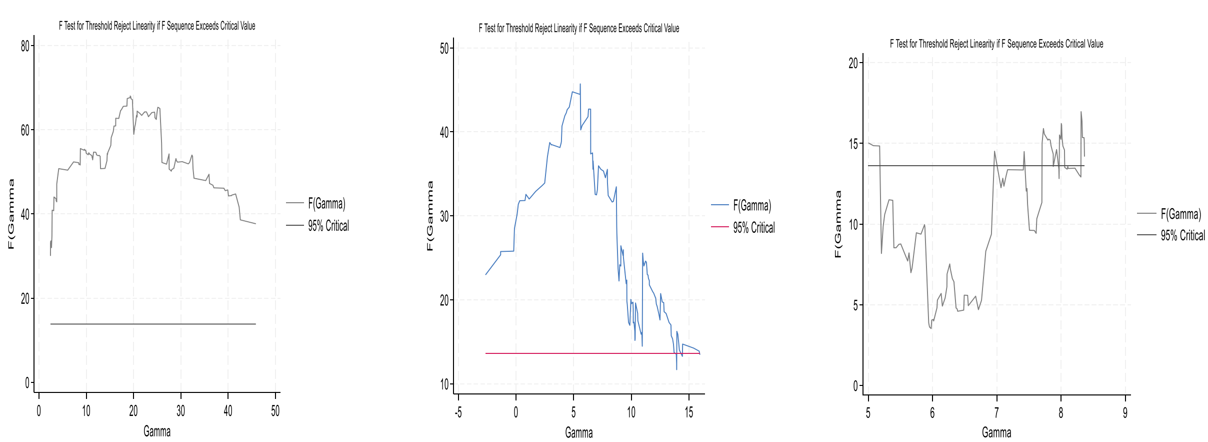
4.3. Empirical estimation

4.3.1. Threshold estimations

4.3.1.1. Test for presence of threshold: dependent variable CO2. Figure 4 provides robust evidence of statistically significant threshold effects in technological innovation, green growth, and green finance, based on tests conducted under the null hypothesis of no threshold against the alternative of a threshold, with heteroskedasticity-consistent (White-corrected) standard errors. The results reveal that the influence of each variable on the outcome is inherently nonlinear, shifting markedly in magnitude or direction once a critical threshold (red line at 5% significant level) is surpassed. This non-uniformity underscores the regime-dependent nature of their effects, validating the application of panel threshold models. Crucially, these findings mark a pivotal turning point – where exceeding critical thresholds in innovation and sustainable development enables resource-dependent economies to break free from the carbon curse and embark on a trajectory that harmonizes economic growth with environmental sustainability.

Figure 5 identifies critical threshold points in the relationships between technological innovation, green growth, and green finance with CO_2 emissions. These thresholds mark the levels at which these variables could trigger or mitigate carbon curse in the region. For technological innovation, the threshold is observed at a value of 4.173, Green growth exhibits a turning point at 6.28, green finance has a threshold at 9.97, indicating the point at which their effect on emissions only becomes meaningful or may even reverse once this level is surpassed.

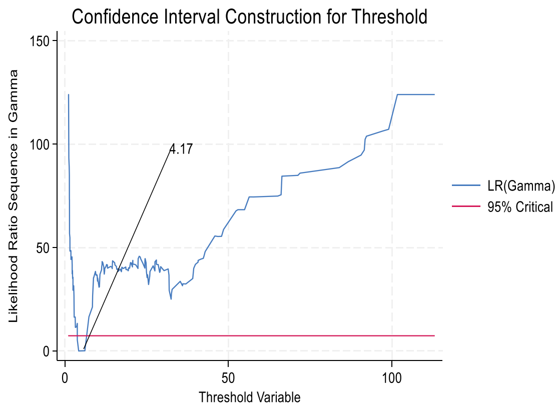
Table 5 provides further evidence of these nonlinear dynamics by comparing global linear models with threshold-based regressions.[4] In the global model, technological innovation shows a small but statistically significant positive effect on emissions, implying that at lower levels, innovation may not be sufficient to



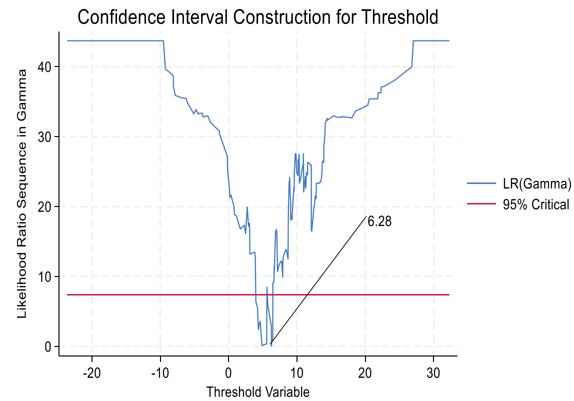
a. Technological Innovation   b. green growth   c. Green Finance

Figure 4. Test for threshold under: null of No threshold against alternative of threshold, allowing heteroscedastic errors (white corrected).

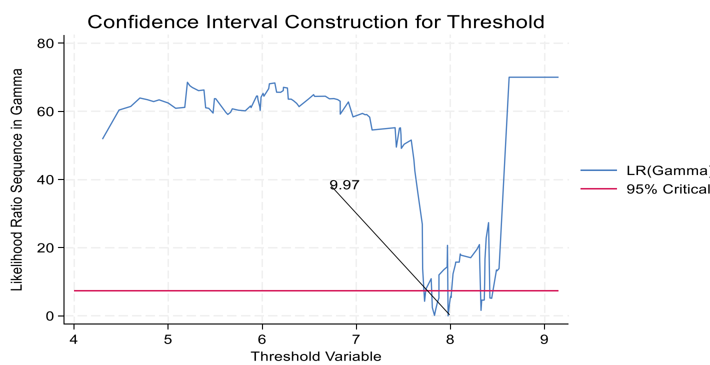
[4]In this modeling structure, we have introduced only environmental impact of economic growth and population without including natural resources rents. This allows a clearer understanding of the baseline relationship between development and environmental degradation, as posited by the Environmental Kuznets Curve (EKC), without confounding it with resource-specific effects. This exclusion also limits insights into the so-called "carbon curse of natural resources" – where resource wealth contributes to higher carbon curse or environmental decay. Therefore, future model extensions in this study will explicitly incorporate resource rents to examine their amplifying role in the development-decay nexus in the selected countries by accounting for the role of Technological Innovation, Green Growth, and Green Finance toward carbon and energy intensity.



Technological Innovation



Green growth



Green Finance

Figure 5. Threshold points for technological innovation green growth and green finance.

Table 5. Threshold regression: CO2 emission as the dependent variable.

	Technological Innovation			Green Growth			Green Finance		
VARIABLES	Global OLS without Threshold	Regime 1 TI<4.173	Regime 2 TI>4.173	Global OLS without Threshold	Regime 1 GG<6.28	Regime 2 GG>6.28	Global OLS without Threshold	Regime 1 GF<9.97	Regime 2 GF>9.97
pop	0.903***	4.347***	1.013***	0.756***	0.977***	1.533***	0.658***	0.662***	12.314***
	(0.057)	(0.411)	(0.053)	(0.058)	(0.088)	(2.967)	(0.052)	(0.059)	(3.612)
gdp	4.756***	18.554	6.624***	5.186***	9.360***	0.674	4.131***	3.985***	0.185**
	(0.732)	(14.895)	(0.622)	(0.828)	(1.298)	(0.073)	(0.850)	(0.971)	(0.134)
gdpsq	−0.612***	−2.557	−0.872***	−0.646***	−1.229***	0.213	−0.499***	−0.465***	−4.089**
	(0.101)	(2.024)	(0.086)	(0.118)	(0.190)	(1.679)	(0.121)	(0.142)	(1.838)
TI	0.007***	−0.025	0.006						
	(0.001)	(0.027)	(0.004)						
GG				−0.009***	−0.002	0.037			
				(0.002)	(0.004)	(0.231)			
GF							0.035***	0.027	0.561**
							(0.014)	(0.017)	(0.253)
Constant	−8.044***	−58.416***	−12.036***	−7.839***	−16.660***	0.005***	−5.563	−5.463***	0.201*
	(1.189)	(25.367)	(0.985)	(1.491)	(2.571)	(0.003)	(1.473)	(1.710)	(0.116)
R.Sq	0.819	0.887	0.898	0.714	0.897	0.596	0.7	0.784	0.142
Heteros: p-value	0.443			0.362			0.150		
Observ	192	45	147	192	67	125	192	141	51

*** if $p < 0.01$, ** if $p < 0.05$, * if $p < 0.1$.

drive decarbonization. However, in the threshold model, the effect of technological innovation becomes insignificant below the threshold, indicating that only high levels of innovation can meaningfully reduce emissions. This finding lends support to the Porter Hypothesis proposed by Porter and Linde (1995), suggesting that stringent environmental regulations can effectively mitigate the carbon curse. It also aligns with emerging evidence from Feng and Li (2019) and X. Zhao et al. (2023) in the context of Chinese provinces. The case of green growth exhibits a similar pattern. While the global model indicates a modest negative effect on emissions, threshold analysis shows that below the critical level of 6.28, green growth has little to no impact. Notably, even above this threshold, the effect turns positive but remains statistically insignificant – potentially reflecting transitional challenges or the lag time needed for benefits to materialize (Pessoa et al. 2025). This finding is consistent with the Porter Hypothesis, which argues that weak environmental policies may impose compliance costs without catalyzing the technological or systemic transformations necessary for decarbonization (Alfalih 2025; W. Zhang et al. 2024). Surprisingly, green finance presents a more complex dynamic. In the global model, it is associated with a significant increase in CO_2 emissions, possibly due to the short-term carbon intensity of initial investments in green infrastructure or technology deployment, as noted by C. W. Su et al. (2024). The threshold model reinforces this interpretation: below a critical threshold, green finance has an insignificant impact, but above it, the effect becomes strongly positive and statistically significant, consistent with findings by C. Zhang et al. (2025). This suggests that while green finance may not yield immediate emissions reductions, it becomes increasingly effective as it matures and reaches a higher level of development or investment.

As anticipated, population exerts a consistently positive pressure on CO_2 emissions across all model specifications, underscoring the necessity for both technological advancement and robust policy innovation to mitigate the environmental impact of demographic expansion, as reported by Khan, Yuan, et al. (2024). The positive coefficient of GDP, coupled with a negative coefficient of GDP squared, provides empirical support for the EKC hypothesis – suggesting that emissions initially rise with economic growth but begin to decline beyond a certain income threshold. This turning point signifies the stage at which resource-rich economies, enabled by higher income levels, can more effectively leverage technological innovation and green finance to decouple growth from CO_2 emissions, reinforcing the finding of Nica, Georgescu, and Kinnunen (2025). As such, escaping the carbon curse of natural resources requires a deliberate policy shift toward sustainable development pathways. Consequently, there is need for targeted green finance mechanisms and accelerate technology adoption to expedite the transition toward the downward trajectory of the EKC. Model diagnostics further validate these findings. The absence of significant heteroskedasticity and the high explanatory power of the models affirm the reliability of the results.

To address the main crux of this study: carbon curse of natural resources, we begin by testing the threshold Points for Technological Innovation, Green Growth, and Green Finance reveals a non-linear relationship between these three variables and both carbon intensity and energy intensity within the modeling structure of natural resource rent as shown in Figure 6 and Table 6 respectively. Figure 6(a–f) indicates that each factor has a threshold level (evidence of sample split), marking a critical turning point where its influence becomes significantly more effective. For example, when technological innovation, green growth and green finance efforts remain below their respective thresholds, they often lack the necessary scale or development to generate significant environmental benefits. However, once these efforts exceed the threshold, they start to play a transformative role substantially reducing emissions and improving energy efficiency through advanced technologies, targeting carbon curse of natural resources neutrality.

The results from the threshold regression Table 6 and graph Figure 7 analysis offer important insights into how technological innovation, green growth, and green finance affect carbon intensity. First, the global OLS estimates present a generalized narrative, as they do not account for threshold effects. As such, a detailed discussion is omitted here and onwards. The threshold model depicts the effectiveness of these environmental and economic strategies shifts once certain critical levels are surpassed. Technological innovation shows a threshold effect at 32.46. Below this level, it is positively associated with carbon intensity, consistent with the rebound effect as noted by York, Adua, and Clark (2022), Uche, Okere, and Das (2023) where efficiency gains increase energy use. Y. Zhao and Wang (2025) further report that outdated technologies in manufacturing can negate innovation's environmental benefits, while Liang, Lin, and Wang (2022) link this dynamic to the carbon curse in resource-dependent economies. However, above the threshold, the relationship turns negative but insignificant, indicating that only mature and widely adopted technologies – such as clean energy systems and efficient industrial processes – effectively reduce emissions from carbon curse. This supports Y. Liu et al. (2023), identifying such innovation as key to achieving carbon neutrality.

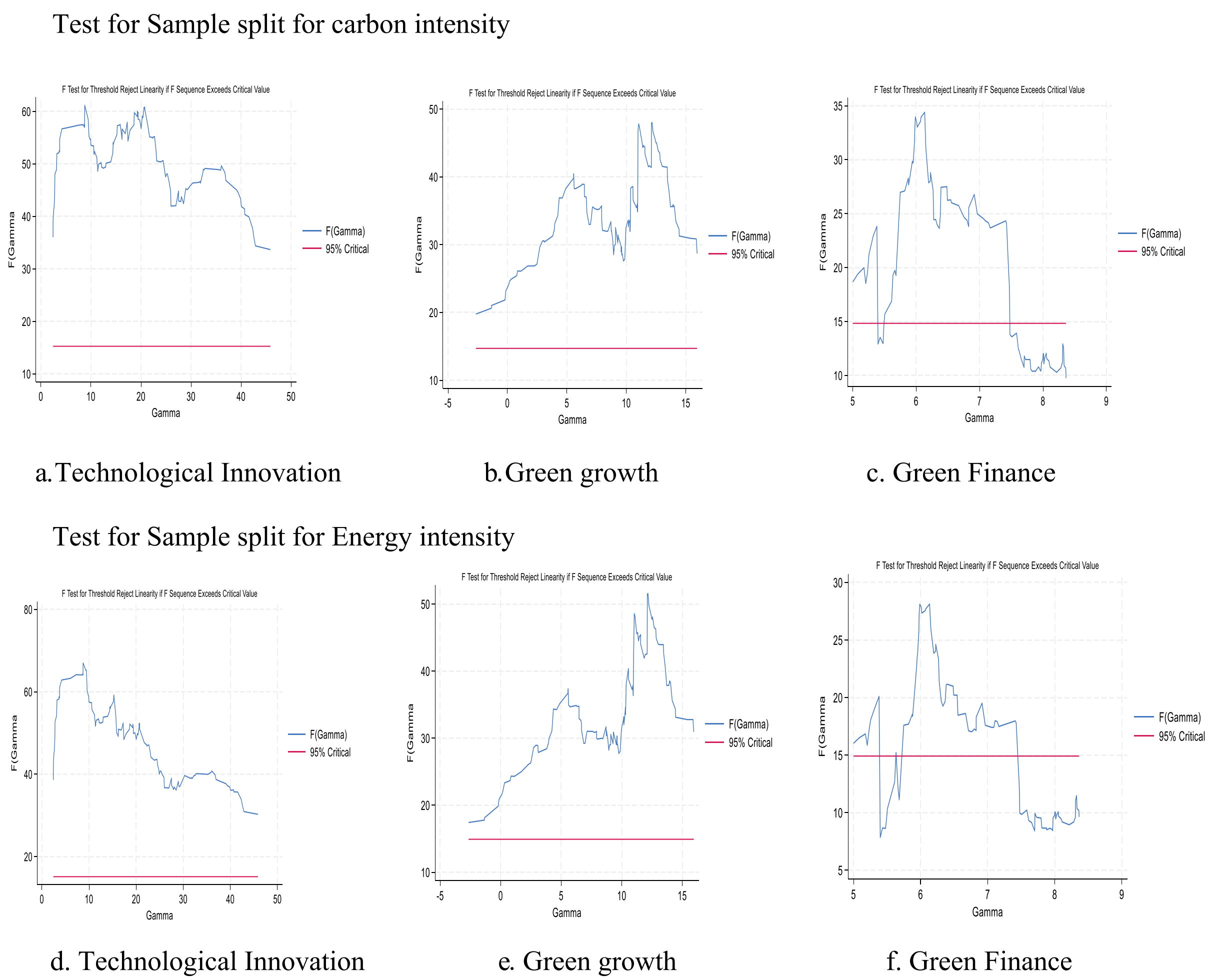


Figure 6. Test for the presence of threshold for technological innovation green growth and green finance.

Table 6. Threshold regression: the dependent variable is carbon intensity.

	Technological Innovation			Green Growth			Green Finance		
VARIABLES	Global OLS without Threshold	Regime 1 TI<32.46	Regime 2 TI>32.46	Global OLS without Threshold	Regime 1 GG<2.72	Regime 2 GG>2.72	Global OLS without Threshold	Regime 1 GF<7.97	Regime 2 GF>7.97
POP	0.209***	0.588***	0.582***	0.170***	−9.706***	0.286***	0.052	−0.040	−0.158**
	(0.070)	(0.149)	(0.208)	(0.073)	(1.890)	(0.085)	(0.060)	(0.062)	(0.053)
GDP	0.677	0.782	10.061***	0.680	0.075	−4.592**	−0.334	1.049	−14.447***
	(0.978)	(1.322)	(2.155)	(0.982)	(0.104)	(1.690)	(0.957)	(0.786)	(1.525)
GDPSQ	−0.162	−0.192	−1.487***	−0.148	5.620***	0.567**	−0.011	−0.180	1.841***
	(0.130)	(0.181)	(0.323)	(0.133)	(0.828)	(0.227)	(0.128)	(0.108)	(0.211)
NR	0.004**	0.002	0.001	0.008***	−0.815	0.014***	0.008***	0.005***	0.011***
	(0.001)	(0.002)	(0.001)	(0.002)	(0.127)	(0.002)	(0.002)	(0.001)	(0.003)
TI	0.005***	0.019***	−0.002						
	(0.001)	(0.004)	(0.001)						
GG				−0.011***	0.002**	−0.020***			
				(0.002)	(0.002)	(0.003)			
GF							0.061***	0.044***	0.027
							(0.013)	(0.013)	(0.059)
Constant	−1.653	−4.536***	−20.165**	−1.413	−0.005**	7.451***	0.781	−1.169	29.298***
	(1.542)	(2.089)	(4.798)	(1.573)	(0.002)	(2.892)	(1.525)	(1.281)	(2.939)
R.Sq	0.405	0.527	0.646	0.538	0.488		0.33	0.242	0.85
Heteros: p-value	0.430			0.263			0.147		
Observ	192	145	47	192	46		192	141	51

*** if $p < 0.01$, ** if $p < 0.05$, * if $p < 0.1$.

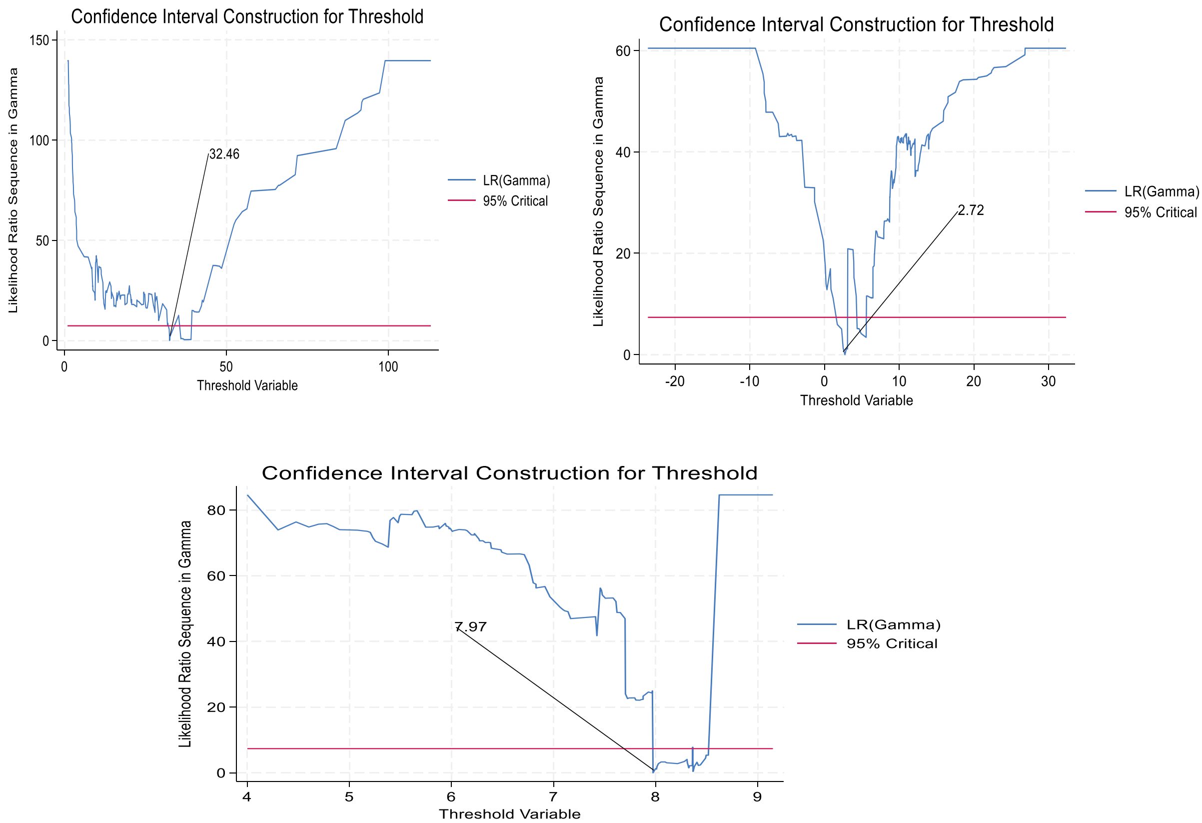


Figure 7. Estimation of threshold points for technological innovation green growth and green finance. carbon intensity as the dependant variable.

Green growth exhibits a threshold effect at 2.72. Below this level, it shows a slightly positive association with carbon intensity, suggesting that early-stage green initiatives may lack the strength to offset emissions. This aligns with the weak decoupling theory and findings by L. Zhang and Ma (2020), where initial efforts fall short of reversing carbon trends. Once green growth exceeds the threshold, the relationship turns strongly negative and statistically significant, indicating a substantial capacity to reduce carbon intensity in more advanced or integrated phases. This supports the strong decoupling trajectory and pathways to escaping the carbon curse, particularly in high-emission regions, as documented by C. Zhang et al. (2025).

The threshold for effective green finance is 7.97. Below this level, green finance shows a positive and significant link to carbon intensity, suggesting that limited or poorly directed funding may support carbon-heavy activities, as seen in China's early green credit programs (J. Zhang, Ke, and Zhang 2022). Above the threshold, the relationship remains positive but becomes statistically insignificant, indicating that while large-scale green finance is essential, its effectiveness depends on (1) strong governance to prevent green-washing and (2) targeted investment in truly low-carbon projects. This aligns with transition theory, which asserts that finance alone is insufficient to drive systemic change without complementary regulatory and technological support. It also reinforces the findings of Xiong et al. (2025), indicating that the impact of green equity on reducing carbon emission intensity is not statistically significant.

The model incorporates natural resource rents (NR), which show a positive and significant effect, confirming the carbon curse – resource-dependent economies tend to have higher carbon intensity due to energy-heavy extraction and slower green transitions (Q. Wang et al. 2024). This supports earlier findings (Y. Li et al. 2022; Nguyen et al. 2023; Qamruzzaman 2024). In such economies, technological innovation below threshold fails to cut emissions, as outdated technologies persist and rebound effects dominate. Likewise, green growth and green finance below thresholds are ineffective without strong governance. The results highlight the difficulty of decarbonizing resource-rich economies and stress the need to exceed key thresholds in innovation, finance, and growth, alongside diversifying resources and reforming institutions to escape carbon curse of natural resources.

Table 7. Threshold regression: dependent variable is energy intensity.

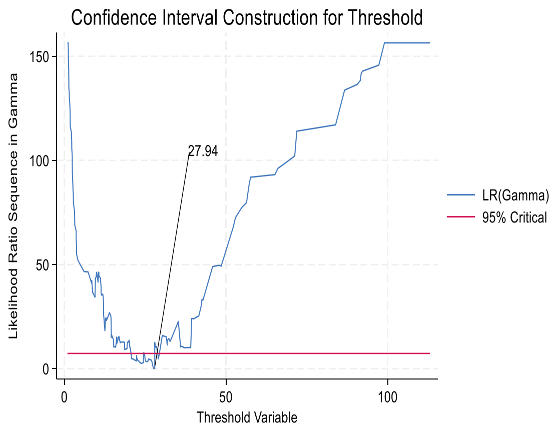
	Technological Innovation			Green Growth			Green Finance		
VARIABLES	Global OLS without Threshold	Regime 1 TI<27.94	Regime 2 TI>27.94	Global OLS without Threshold	Regime 1 GG<3.06	Regime 2 GG>3.06	Global OLS without Threshold	Regime 1 GF<7.97	Regime 2 GF>7.97
POP	4.069***	7.050***	8.015	3.656***	2.653**	5.367***	2.092**	0.768	3.352
	(1.061)	(1.900)	(17.656)	(1.100)	(1.526)	(1.229)	(0.908)	(0.749)	(3.161)
GDP	−18.023	13.05	74.419	−16.683	63.600***	−91.802***	−30.715***	−5.390	−368.257**
	(15.428)	(14.931)	(202.911)	(15.478)	(13.045)	(25.583)	(14.883)	(10.541)	(24.277)
GDPSQ	1.368	−2.99	−30.487***	1.358	−9.607***	11.564***	3.269	0.019	48.590***
	(2.057)	(2.011)	-(12.070)	(2.093)	(1.974)	(3.428)	(1.982)	(1.427)	(3.477)
NR	0.097***	0.080***	−0.076**	0.144***	0.053***	0.247***	0.146***	0.113***	0.246***
	(0.024)	(0.026)	(0.043)	(0.026)	(0.025)	(0.033)	(0.024)	(0.021)	(0.054)
TI	0.063***	0.280***	−0.056***						
	(0.008)	(0.048)	(0.023)						
GG				−0.140***	−0.009	−0.330***			
				(0.026)	(0.037)	(0.050)			
GF							0.772***	0.534***	−3.113***
							(0.205)	(0.139)	(0.976)
Constant	21.081	−58.12**	−437.694**	21.335	−115.736**	147.371***	51.642***	14.414***	698.564***
	(24.450)	(23.479)	(172.236)	(24.824)	(29.897)	(44.245)	(23.791)	(17.237)	(33.892)
R.Sq	0.643	0.508	0.704	0.380	0.431	0.610	0.368	0.318	0.973
Heteros: p-value	0.866			0.281			0.235		
Observ	192	133	59	192	48	144	192	172	20

*** if $p < 0.01$, ** if $p < 0.05$, * if $p < 0.1$.

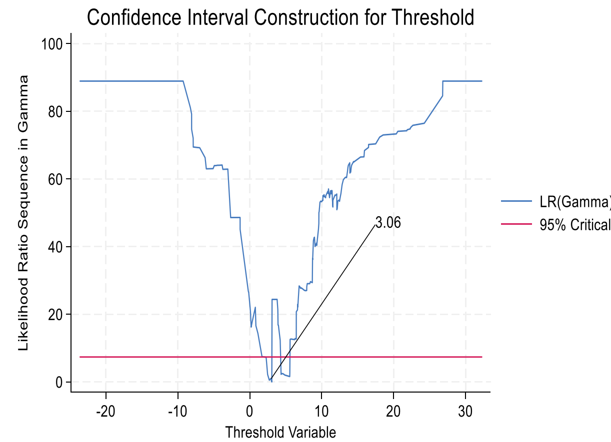
The threshold regression results in Table 7 and Figure 8 examine the effects of technological innovation (TI), green growth, and green finance on energy intensity, identifying distinct threshold levels for each variable to offer a more detailed understanding of their environmental impacts. Notably, when a country's technological innovation falls below the threshold of 27.94, it is associated with a positive and significant effect on energy intensity, with a coefficient of 0.280. This implies that early-stage, innovation may inadvertently increase energy use, likely due to the deployment of inefficient or energy-intensive technologies, or limited diffusion of energy-saving practices. However, once innovation surpasses the 27.94 threshold, the relationship turns negative and statistically significant, suggesting that mature and advanced innovation – characterized using energy-efficient technologies and optimized production systems – can play a critical role in reducing energy intensity or mitigating carbon curse. These findings reinforce earlier results related to carbon intensity and align with emerging empirical evidence from Y. M. Li et al. (2023) and Irandoust (2019), which emphasize the importance of technological maturity in achieving sustainable energy transitions and escaping the carbon curse of natural resources.

A comparable pattern is observed for green growth, with a threshold identified at 3.06. Below this level, green growth exerts no statistically significant effect on energy intensity – a finding that resonates with insights from decoupling theory and ecological modernization theory. This suggests that early-stage green growth initiatives may lack the institutional coherence, financial scale, or technological depth necessary to influence energy consumption patterns in a meaningful way. As argued by Mahmood, Ullah, and Mumtaz (2021) and Alfalih (2025), such policies often remain fragmented, underfunded, or largely symbolic, failing to catalyze systemic change. However, once green growth surpasses the 3.06 threshold, its impact becomes strongly negative and statistically significant, indicating a shift toward mature, integrated, and transformative policy frameworks and possibly as pathways to escaping the carbon curse. This reinforces the argument that only at higher levels of strategic coordination and implementation can green growth serve as a catalyst for reducing energy intensity across economies (Alfalih 2025).

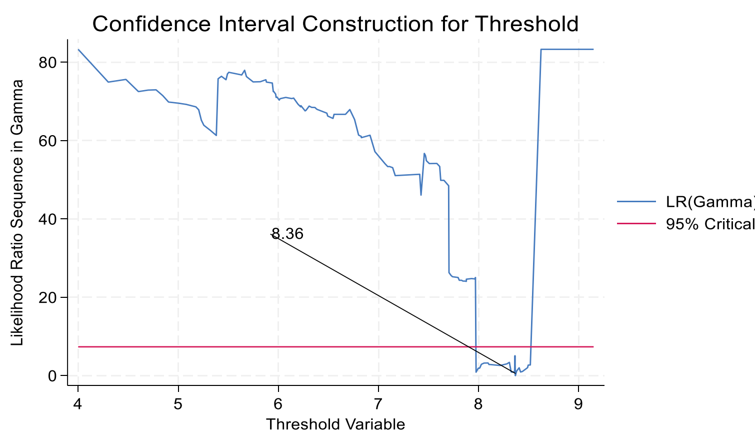
For green finance, the analysis identifies a threshold at 7.97. Below this level, it is positively and significantly associated with energy intensity, consistent with Resource Allocation Theory and Ecological Modernization Theory. This suggests that poorly targeted or weakly institutionalized green finance may support projects that fail to improve energy efficiency or offer pathways to escaping carbon curse. Above the threshold, the relationship turns strongly negative and significant, indicating that adequate and well-directed green finance effectively reduces energy intensity by supporting pathways to escaping carbon curse, renewables, sustainable infrastructure, and low-carbon technologies. Evidence from China (An et al.



a. Technological Innovation



b. Green growth



c.Green Finance

Figure 8. Estimation of threshold points for technological innovation green growth and green finance. Energy intensity as the dependant variable.

2023) supports this, showing that green finance only lowers energy intensity when its index exceeds a threshold, highlighting the importance of scale and strategic allocation.

Finally, natural resource rent (NR) shows a consistently positive and significant relationship energy intensity across all regimes. This supports the concept of the resource intensity trap and the broader carbon curse, where resource-dependent economies consume more energy due to extractive processes and slow transitions to low-energy structures. This finding reinforces the study's core argument: surpassing the thresholds of technological innovation, green growth, and green finance offers critical pathways for resource-rich economies to escape carbon curse and advance toward low-carbon, energy-efficient development.

4.4. Robust check and further discussion

This section as shown in Table 8 provides a detailed explanation of how natural resources interact with technological innovation, green growth, and green finance to influence the carbon curse trajectory in the selected economies – specifically in terms of carbon emissions (CO_2), carbon intensity (CI), and energy intensity (EI). While the direct effects of variables like population and GDP align with earlier findings, the interaction terms offer deeper insights into relationships that are critical for informing sustainable policy strategies.

Table 8. Robust check via Panel-corrected standard errors.

VARIABLES	CO2 1	CO2 2	CO2 3	CI 4	CI 5	CI 6	EI 7	EI 8	EI 9
POP	0.903***	0.756***	0.658***	0.149***	0.143**	0.056	3.252***	3.302***	2.150***
	(16.870)	(13.670)	(13.410)	(2.597)	(2.361)	(1.087)	(3.859)	(3.683)	(2.758)
GDP	4.756***	5.186***	4.131***	0.118	0.072	−0.292	−25.870*	−24.770*	−30.230**
	(7.062)	(5.596)	(4.842)	(0.124)	(0.073)	(0.313)	(1.774)	(1.649)	(2.126)
GDPSQ	−0.612***	−0.646***	−0.499***	−0.079	−0.067	−0.012	2.527	2.434	3.254*
	(6.513)	(4.883)	(4.083)	(0.606)	(0.489)	(0.096)	(1.252)	(1.164)	(1.650)
NR				0.001	0.011***	−0.013***	0.061**	0.183***	−0.124**
				(0.603)	(6.469)	(3.370)	(2.260)	(7.354)	(2.105)
TI	0.007***								
	(11.080)								
GG		−0.009***							
		(4.220)							
GF			0.034***						
			(2.596)						
NR*TI				0.002***			0.002***		
				(7.578)			(5.828)		
NR*GG					−0.004***			−0.005***	
					(6.433)			(5.819)	
NR*GF						0.003***			0.041***
						(5.454)			(4.555)
Constant	−8.044***	−7.839***	−5.563***	−0.181	−0.171	1.017	41.29	37.85	54.69**
	(7.130)	(4.495)	(3.629)	(0.109)	(0.098)	(0.626)	(1.596)	(1.419)	(2.171)
Observations	192	192	192	192	192	192	192	192	192
R-squared	0.819	0.715	0.7	0.342	0.339	0.348	0.368	0.382	0.38
No. of c_id	8	8	8	8	8	8	8	8	8
chi2	1052	693.9	679.6	167.3	103.6	105.6	148.4	109.1	107.1

*** if $p < 0.01$, ** if $p < 0.05$, * if $p < 0.1$.

The interaction between natural resources and technological innovation reveals a double-edged effect, on one hand, showing a consistent positive and significant impact on both CO_2 emissions and energy intensity. This suggests that in resource-rich contexts, technological innovation may intensify the carbon curse rather than mitigate it. This counterintuitive outcome likely reflects a scale effect, where innovation boosts production and extraction efficiency without necessarily reducing carbon emissions. Similar findings in Malaysia by Ehigiamusoe et al. (2024) report that technological innovation fails to offset the environmental impact of natural resource rents. On the other hand, this pattern does not hold for carbon intensity, implying that while emissions and energy use are rising, emissions per unit of energy consumed remain relatively stable. This points to a technological gap – current innovation may be energy-saving but not yet emissions-reducing, aligning with observations by Garrone and Grilli (2010).

In contrast, the interaction between natural resources and green growth emerges as a mitigating force-consistently negative and significant influence across all three environmental metrics – CO_2, CI, and EI. This implies that green growth enables countries to decouple economic advancement from environmental degradation and move toward escaping carbon curse (Dam et al. 2024). The findings support the argument that integrating environmental objectives into economic planning – such as through energy efficiency, cleaner technologies, and sustainable industrial policies – can effectively reduce the carbon curse of natural resources of resource-rich countries. The interaction between natural resources and green finance somewhat complex is positively and significantly associated with both CO_2 emissions and energy intensity, and also with carbon intensity. This suggests that current green finance allocations may not be effectively targeting emissions-reducing initiatives, or that such investments have long gestation periods before delivering environmental benefits.

5. Conclusion and policy recommendations

This study investigates threshold and the interaction effect models to understand how technological innovation (TI), green growth (GG), and green finance (GF) influence environmental outcomes in resource-rich economies. This study interrogates the existing evidence and offers some masterpiece pathways for escaping the Carbon Curse of Natural Resources. Using a dataset from 2000–2023, Hansen (1999) threshold model and Panel-Corrected Standard Errors as a robust check, the key findings as reported in Appendix 2 are as follows: Firstly, natural resources (NR) are positively linked to CO_2 and intensities across all models, affirming the carbon curse. In the interaction model, TI increases CO_2 and energy intensity, suggesting that innovation alone is insufficient for decarbonization. The threshold model confirms this: below a critical level (TI < 32.46/27.94), innovation worsens environmental performance, while above it, the effect turns mildly negative indicating only mature, widely adopted technologies reduce emissions. GG consistently lowers emissions in the linear model. However, threshold results show limited or no effect below a threshold (2.72–6.28). Only at higher levels does GG significantly reduce carbon and energy intensity, supporting the view that policy maturity is essential. GF has a positive effect on emissions in the interaction model. Threshold analysis reveals this is true below a 7.97 threshold, while above it, the effect weakens or reverses. This implies early-stage green finance may be ineffective or misallocated.

5.1. Policy recommendations

The findings of this study offer compelling support for the policy position that natural resource dependence is positively associated with elevated CO_2 emissions and intensities, thereby reinforcing the presence of a carbon curse in resource-rich economies. To mitigate this phenomenon, policy frameworks should prioritize strategic investments in technological advancement and energy efficiency aimed at reducing carbon dependency. This includes the adoption and diffusion of energy-efficient technologies, as well as structural economic diversification away from carbon-intensive sectors. Critically, the evidence indicates that technological innovation alone is insufficient unless it reaches a threshold of maturity and widespread adoption. Thus, policy interventions should focus on supporting the commercialization and scaling of low-carbon technologies, ensuring that innovation translates into measurable emission reductions. Additionally, maintaining energy consumption below identified critical thresholds is essential to avoid rebound effects that may undermine progress. Sector-specific targeting – particularly in high-emitting industries such as iron and steel, cement, chemicals, and pulp and paper – is imperative for comprehensive decarbonization. Interestingly, green growth holds considerable promise for reconciling economic development with environmental sustainability, achieving absolute decoupling remains a formidable challenge. To align green growth with global mitigation goals, including mitigating carbon curse, governments must intensify efforts to scale up climate investments, implement carbon pricing, and foster innovation and behavioral change. Finally, green finance offers significant potential to support emission reductions, its effectiveness is contingent upon developmental stage and regional context. Policymakers must ensure strategic and targeted allocation, particularly during early phases, to prevent misallocation and enhance its transformative impact. In all, these policy directions represent critical levers for escaping the carbon curse and advancing toward a sustainable, low-carbon future.

5.2. Limitations and future direction

While the research made several notable contributions to the literature, there are some limitations that must be recognized. First, owing to the lack of on green finance and technological innovation across 2000–2023 period, the study was limited to only 8 resource-rich economies. In the future, subsequent studies should revisit the conclusions of this study using more updated datasets as they become available. Second, while this research explores green growth, technological innovation and green finance as vital de-cursing instruments, it however did not account for other potentially pertinent factors like energy security, green taxes, institutional quality among others. The utilization of these variables in future research can produce deeper insights on the channels through which the carbon curse can be mitigated. Lastly, the current study exclusively focused on resource-endowed nations, where the carbon curse could be more intense and this constrains the generalizability of the conclusions to other economies particularly those with diversified resources or less reliant on natural wealth. This study can be replicated in the future across different regional or country contexts.

Author contributions

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Appendices

Appendix 1. Skewness and kurtosis tests for normality/Shapiro–Wilk W test for normal data

Variable	Obs	Pr(skewness)	Pr(kurtosis)	Adj chi2(2)	Prob > chi2	W	V	z	Prob > z
CO2	192	0.007	0.014	11.540	0.003	0.951	7.005	4.470	0.000
CI	192	0.000	0.000	72.220	0.000	0.782	31.391	7.914	0.000
EI	192	0.000	0.000	89.810	0.000	0.739	37.530	8.324	0.000
POP	192	0.001	0.000	20.330	0.000	0.910	13.022	5.893	0.000
GDP	192	0.046	0.008	9.760	0.008	0.960	5.742	4.013	0.000
NR	192	0.002	0.854	8.650	0.013	0.954	6.592	4.330	0.000
TI	192	0.000	0.000	47.700	0.000	0.801	28.623	7.702	0.000
GG	192	0.825	0.216	1.600	0.450	0.977	3.366	2.787	0.003
GF	192	0.235	0.000	56.270	0.000	0.946	7.806	4.718	0.000

Appendix 2. Summary of findings

Variable	Interaction Model (Linear Global Model)	Threshold Model	Interpretation
Technological Innovation (NR*TI)	Positive and significant impact on CO_2 and EI	Below threshold (32.46/27.94): increases CI and EI; Above: reduces emissions/energy but insignificantly	Innovation without maturity leads to higher emissions/energy use; Only advanced/mature TI helps decarbonization
Green Growth (NR*GG)	Negative and significant across CO_2, CI, EI	Below threshold (2.72–6.28): no or positive impact; Above: strong negative impact on CI and EI	Green growth benefits only materialize after maturity; aligns with strong decoupling theory
Green Finance (NR*GF)	Positive and significant for CO_2, CI, EI	Below threshold (7.97): worsens intensities; Above: turns negative/insignificant	Early green finance may worsen emissions; effectiveness requires scale, direction, governance
Natural Resources (NR)	Mixed signs: insignificant to significant depending on model	Positive and significant across all models	Confirms the carbon curse – resource dependence leads to higher emissions and intensity
Population & GDP (incl. EKC)	POP positive; GDP positive, GDP^2 negative (EKC confirmed)	Same pattern; richer economies leverage TI and GF better	Economic structure matters – richer economies can escape carbon curse with aligned policies