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Decoupling growth from degradation: a CS-ARDL and MMQR panel analysis of ecological footprints and sustainable economic growth

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This study examines how natural resource rents, technological advancement, renewable energy use, and economic growth affect ecological footprints in ten developing economies (Brazil, China, Bangladesh, South Africa, India, Pakistan, Indonesia, Mexico, Russia, and Ethiopia) from 1990 to 2020. Using advanced econometric techniques, including CS-ARDL and MMQR models, the analysis tests both long-run and distributional relationships while addressing cross-sectional dependence and heterogeneity. The results indicate that renewable energy use and technological innovation significantly reduce ecological footprints, supporting the Environmental Kuznets Curve hypothesis in these contexts. Additionally, environmental taxes and regulations are found to mitigate environmental degradation effectively. However, continued reliance on fossil fuels remains a major challenge for these economies. The study's findings highlight the need for stronger environmental governance, investment in green technologies, and policy reforms to promote sustainable development. By providing robust empirical evidence, this research contributes to the literature on sustainable growth strategies in resource-dependent developing countries.

KEYWORDS

green growth, GDP, renewable energy, technological innovation, green economies

1 Introduction

Sustainable development aims to achieve economic growth without degrading the ecological foundations on which societies depend, underscoring the need to embrace ecological sustainability (Li et al., 2023). This requires avoiding the unsustainable extraction of natural resources without investing in environmentally friendly infrastructure, cleaner production methods, and greener supply chains (Abbasi et al., 2021; Ahmed et al., 2020a). Climate action and green development are increasingly seen as two sides of the same coin, making the concept of green economies central to contemporary policy debates (Awosusi et al., 2022). Yet many less-developed countries continue to exhibit weak measures for environmental sustainability, resulting in lower sustainable growth, higher pollution rates, and limited progress toward climate goals. This calls for a shift toward well-designed, eco-friendly economic policies that can reduce pollution and minimize energy losses (Appiah et al., 2023; Bölük et al., 2014).

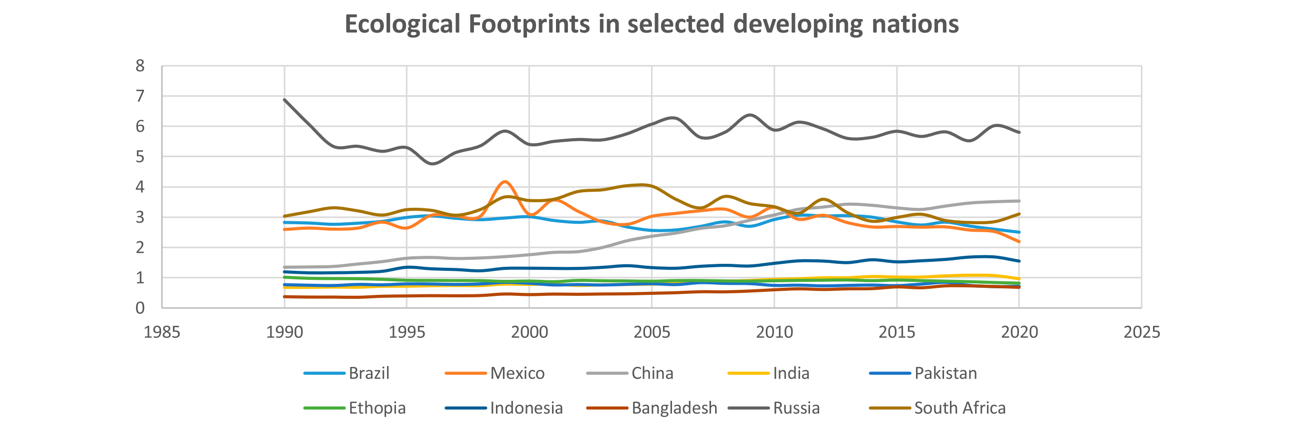

FIGURE 1
Ecological footprints of selected developing nations.

Despite growing awareness, many developing economies show insufficient concern for sustainable natural resource consumption in their environmental governance frameworks. Weak enforcement of environmental laws often leads to resource overuse and ecological degradation, exacerbating social and economic vulnerabilities (Adams and Nsiah, 2019; Afolabi, 2023). The "crowding-out" effect where excessive reliance on natural resources can undermine economic diversification and sustainability remains a persistent barrier (Badida et al., 2023). As a result, many economies struggle to reconcile economic growth with environmental protection, failing to meet sustainability targets or international commitments such as the COP28 goals.

Recent years have seen growing recognition of the need for stricter environmental policies and sustainable practices to mitigate the negative impacts of fossil fuel dependence and other conventional energy sources (Chien et al., 2021; Bamati and Raoofi, 2020). Many countries are turning to new technologies to replace older, more polluting methods of production, seeking to minimize environmental damage and improve air quality (Alola et al., 2019; Alam et al., 2021). Expanding the use of renewable energy is also critical for transitioning to low-carbon economies and achieving the targets of international climate agreements (Irfan et al., 2022). Several studies have highlighted the complex and sometimes contradictory relationships between renewable energy use, technological innovation, natural resource exploitation, and environmental outcomes (Agboola et al., 2021; Ahmad et al., 2020). While green innovation can significantly reduce carbon emissions and ecological degradation (OECD, 2021; Salahuddin et al., 2018), the effectiveness of these measures varies across contexts, particularly in developing economies with high levels of resource dependence.

This study is motivated by the urgent policy challenge of decoupling economic growth from environmental degradation in resource-dependent developing economies. Despite global commitments such as the COP28 goals, many of these countries continue to rely heavily on natural resource rents and fossil fuels, lacking effective governance mechanisms to promote green innovation and renewable energy adoption. This results in rising ecological footprints, threatening long-term sustainability and social welfare. Addressing this problem requires robust empirical evidence on how policy-relevant factors natural resource dependence, technological advancement, renewable energy use, and economic growth interact to shape environmental outcomes in these contexts (Cai et al., 2025). Figure 1, illustrates the trends in ecological footprints across ten developing countries in the sample, highlighting variations in environmental impact and underscoring the need for differentiated policy responses to manage sustainability challenges.

However, despite increased policy focus and emerging initiatives, there remains a significant gap in empirical understanding of how natural resource rents, renewable energy use, technological innovation, and economic growth jointly influence ecological footprints in developing economies. Much of the existing research focuses on developed countries or examines these factors in isolation (Ali et al., 2021; Adebayo et al., 2023; Balsalobre-Lorente et al., 2018). This neglects the specific challenges faced by developing nations that rely heavily on natural resource exploitation and have weaker institutional capacities for enforcing sustainability measures.

The sample of ten major developing economies (Brazil, China, Bangladesh, South Africa, India, Pakistan, Indonesia, Mexico, Russia, and Ethiopia) is intentionally selected to reflect diverse but comparably resource-dependent nations that face similar sustainability challenges. The findings aim to inform both country-specific and generalizable policy strategies by revealing shared dynamics and heterogeneity in the drivers of ecological degradation. Unlike much of the existing literature, which either focuses on advanced economies or examines these factors in isolation, this study integrates them within a unified empirical framework using advanced econometric methods (CS-ARDL and MMQR). This approach allows us to identify both average and distributional effects across countries and income levels, offering novel insights into the potential for green transitions in developing economies.

This study seeks to address this research gap by examining the relationships among natural resource rents, renewable energy use, technological advancement, and GDP growth in ten developing economies (Brazil, China, Bangladesh, South Africa, India, Pakistan,

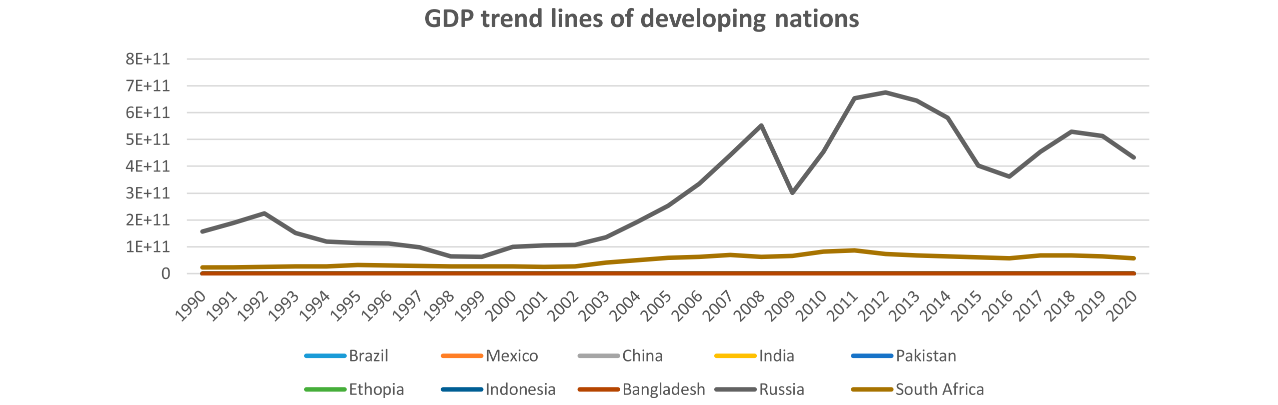

FIGURE 2
Current trends of GDP growth in selected developing nations.

Indonesia, Mexico, Russia, and Ethiopia) from 1990 to 2020. By applying advanced econometric methods including the CS-ARDL and MMQR models this analysis aims to generate robust, policy-relevant evidence to inform strategies that can help decouple economic growth from environmental degradation, support green innovation, and advance the transition toward sustainable development in these emerging economies. Figure 2, shows GDP growth trajectories across the sample countries, contextualizing their economic development patterns.

This study makes several important contributions to the literature on environmental sustainability and economic development in emerging economies. Empirically, it provides new evidence on the relationship between ecological footprints, natural resource rents, renewable energy use, technological innovation, and GDP growth across ten developing countries from 1990 to 2020, using advanced econometric techniques such as CS-ARDL and MMQR to capture both average and distributional effects (Wang et al., 2022; Rafique et al., 2022). This approach addresses the lack of robust, country-level panel analyses for developing economies, many of which remain highly dependent on natural resource extraction but lack adequate environmental governance frameworks.

Theoretically, the study extends the Environmental Kuznets Curve hypothesis by integrating variables related to green innovation and renewable energy, testing whether these factors can modify the traditional inverted U-shaped relationship in contexts with weaker institutions (Environmental Kuznets Curve Hypothesis, 2025; Al-Mulali et al., 2015). Conceptually, the paper offers a more holistic framework by simultaneously examining the roles of economic growth, technological change, and environmental governance in decoupling development from environmental degradation, aligning with recent calls in the literature for integrated sustainability assessments (Asongu and Odhiambo, 2020; Adebayo et al., 2022). Unlike existing studies that typically focus on single factors or advanced economies, this research highlights the unique challenges and policy trade-offs faced by developing nations striving for green growth (Xu et al., 2025). By doing so, it offers actionable insights for policymakers aiming to achieve the COP28 goals and broader sustainable development objectives in resource-dependent, rapidly industrializing economies (Agency IRENA, 2024). The next part of this study is organized into four sections. Section 2 presents the literature review. Section 3 describes the methodology, theoretical framework, and data. Section 4 discusses the results and arguments. Finally, Section 5 provides the policy implications and concluding remarks.

2 Literature review

To strengthen the empirical foundation of this study, we review recent panel studies that examine the link between economic growth, natural resource use, renewable energy, technological innovation, and environmental outcomes in developing and developed economies. For example (Adebayo et al., 2022), used a non-linear ARDL approach to show that technological innovations and renewable energy reduce carbon emissions in remittance-receiving countries. The study (Abbasi et al., 2021) employed advanced panel estimation to demonstrate that natural resources and economic growth drive ecological footprints in developing economies. Another study (Cao et al., 2022) applied spatial Durbin models to highlight the role of the digital economy in improving energy development in China. A study by (Khan et al., 2023) investigated natural resource rents and CO_2 emissions in G7 countries using dynamic panel techniques, finding evidence of the resource curse mitigated by green growth policies. In the same way (Bildirici and Kayıkçı, 2013) analyzed Asian countries with ARDL models to demonstrate that financial development and technology significantly influence environmental sustainability. These studies use diverse methodologies such as CS-ARDL, FMOLS/DOLS, quantile regressions, and spatial econometrics to reveal complex, often non-linear relationships between economic variables and environmental degradation.

2.1 Ecological damage and economic growth

We examine the relationship between ecological degradation and economic development, using GDP as an indicator of growth. The study by (Grossman and Krueger, 1995) demonstrates an inverted U-shaped curve describing this relationship, suggesting that ecological degradation initially rises with increasing *per capita* income but declines after reaching a certain threshold (Cai et al., 2025).

A recent study (Adebayo et al., 2023) focuses on renewable energy and environmental issues, concluding that participation in international trade and the use of renewable energy for electricity generation support the Environmental Kuznets Curve (EKC) hypothesis. This underscores the role of commerce in introducing new products and technologies capable of mitigating environmental problems.

Another study (Balsalobre-Lorente et al., 2018) investigates the relationship between population dynamics, economic growth, and CO_2 emissions at the global level, noting that urban densities in Southeast Asia, the Americas, and Europe have significantly increased due to city growth. Policymakers were advised to consider the implications of GDP growth for environmental management. Additionally (Zhang et al., 2022), provides an overview of relevant literature, while (Bölük et al., 2014) presents a study evaluating the environmental impacts of energy use, with an emphasis on the roles of renewable and fossil energy sources.

2.2 Environmental degradation and natural resources

The literature review establishes that natural resources exert significant influence on both economic development and environmental sustainability, as proposed by (Wang et al., 2022) and supported by (Bamati and Raoofi, 2020). This framework suggests an inverse relationship between resource dependence and overall development. Moreover, many developed countries with abundant resources continue to export raw materials to wealthier nations with advanced technologies instead of processing them domestically. Several studies indicate that natural resource extraction tends to negatively affect GDP growth in developing countries, while outcomes are relatively more favorable in developed economies (Rafique et al., 2022).

To investigate the role of natural resources in economic performance (Environmental Kuznets Curve Hypothesis, 2025), employed comprehensive analyses using DOLS and ARDL tests and found that economic growth in China leads to natural resource depletion. Similarly (Al-Mulali et al., 2015), extended their research to analyze the impact of variables such as urbanization, energy consumption, CO_2 emissions, and economic growth in two countries, finding strong links between energy consumption, GDP, urbanization, and carbon dioxide emissions (Shang and Luo, 2021).

In this study, the CS-ARDL model was applied to data from 1990 to 2020. The analysis revealed evidence of a U-shaped Environmental Kuznets Curve (EKC), challenging the notion of a simple link between economic growth and environmental decline. According to these results, for such economies to achieve the targets set in the COP26 agreement, it is essential to implement effective measures to minimize natural resource consumption. Many developed countries have pursued this approach by adopting cleaner technologies and more efficient energy use.

Additionally, using data for 283 Chinese regions from 2004 to 2017 (Asongu and Odhiambo, 2020), explored the phenomenon of the CO_2 effectiveness curse, finding that higher natural resource utilization results in increased CO_2 emissions. Using natural resources while promoting clean technology was shown to reduce the efficiency of carbon emission reduction. Similarly (Adebayo et al., 2022), examined pollution and GDP development in ASEAN countries, revealing that high GDP and population growth jointly slow the decoupling process, suggesting that achieving significant emissions reductions may take considerable time.

Further (Xu et al., 2025), addressed the issue of natural resource degradation and ecological efficiency by exploring the correlation between natural resources, economic growth, environmental protection, clean energy, and technology in OECD nations. Using CO_2 emissions as an indicator of ecological damage from 1989 to 2021, their empirical evidence suggests that the effect of natural resources on ecological sustainability is gradual but significant. The EKC hypothesis was observed in OECD countries, where results indicated that CO_2 emissions negatively impact natural resource utilization. According to these findings, transitioning to clean energy sources is essential to ensure ecological sustainability and meet the goals of COP26 (Ahakwa et al., 2024).

2.3 Environmental degradation and technological innovation

Several studies have indicated that it is possible to drastically reduce CO_2 emissions through technological advancements, particularly in industrial processes, without hindering economic growth. For example (Asongu and Odhiambo, 2020), explored the link between air pollution and renewable energy development in China, finding that the implementation of innovation and clean energy significantly reduces air pollution. Research on environmental degradation in rapidly industrializing countries also affirms that accelerating innovation can substantially mitigate ecosystem damage. According to (Agency IRENA, 2024), technological transformation is essential for achieving a clean environment and advancing the sustainable development agenda (Duan, 2025). Similarly, studies on China have found a strong correlation between innovation and ecological conservation, concluding that the adoption of green technology is vital for meeting Sustainable Development Goals.

For instance (Cao et al., 2022), focused on trends in alternative oil consumption, natural resources, and energy use in European countries between 1996 and 2016. Their analysis indicated that varying proportions of oil utilization reduce price sensitivity and thereby restrict the growth of renewable energy usage. The study emphasizes the need to incorporate sufficient clean energy sources and carbon sequestration technologies into regional energy transition policies to reduce reliance on nonrenewable energy. Their findings also showed that the Environmental Kuznets Curve (EKC) pattern (Kuznet, 2025) was more dominant in countries with lower carbon emissions, while only high-emitting countries exhibited clear signs of EKC behavior. Furthermore, their research did not establish any significant correlation or interaction between nexus expansion and environmental outcomes. According to (Awosusi et al., 2022), technological innovation positively impacts

TABLE 1 Empirical literature review.

Study	Variables examined	Econometric methodology	Countries/ Regions	Key findings
Adebayo et al. (2023)	Technological innovation, renewable energy, globalization, remittances, CO_2 emissions	Non-linear ARDL	Top 10 remittance-receiving countries	Renewable energy and technology reduce emissions in the long run
Ahmad et al. (2020)	Natural resources, GDP, technological innovation, ecological footprint	Advanced panel estimation	Developing economies	Natural resource dependence increases ecological footprint
Wang et al. (2022)	Digital economy, energy development	Spatial Durbin Model	China	Digital economy improves high-quality energy development
Khan et al. (2023)	Natural resources, CO_2 emissions, green growth	Dynamic Panel Techniques	G7 countries	Resource curse mitigated by green growth policies
Saleem et al. (2020) (Duan, 2025)	Financial development, energy demand, technology, environment	ARDL Model	Selected Asian countries	Financial development and technology improve environmental sustainability
Akram et al. (2020) (Al-Mulali et al., 2015)	Energy efficiency, renewable energy, CO_2 emissions	Non-linear Panel ARDL	BRICS economies	Renewable energy and efficiency reduce emissions in the long run
Danish et al. (2017) (Agency IRENA, 2024)	Renewable vs non-renewable energy, GDP, EKC	Cointegration, Causality Analysis	Pakistan	EKC supported; renewable energy reduces emissions
Alola et al. (2019)	Trade policy, economic growth, fertility rate, energy use, ecological footprint	Panel Data Analysis	Europe	Trade and energy use increase ecological footprint
Adedoyin et al. (2020) (Wang et al., 2022)	Economic expansion, R&D, environmental sustainability	Panel Cointegration, Granger Causality	EU countries	Economic growth and R&D reduce emissions in the long run
Liu et al. (2023) (Zhang et al., 2022)	Urbanization, energy consumption, GDP, CO_2 emissions	ARDL Model	China	Urbanization and GDP increase emissions; renewable energy mitigates it
Alam et al. (2021)	R&D investment, stock markets, clean energy, CO_2 emissions	Advanced Panel Techniques	OECD economies	R&D investment and financial development reduce CO_2 emissions
Appiah et al. (2023)	Environmental policy, renewable energy, innovation, ecological footprint	Dynamic Panel System GMM	Global sample	Environmental policies and renewable energy reduce ecological footprints
Irfan et al. (2022)	Green finance, green innovation	Spatial econometrics	China	Regional policy interventions strengthen green finance and innovation effects
An et al. (2021)	Technology innovation, connectivity, CO_2 emissions	MMQR	Belt and Road countries	Innovation and connectivity reduce emissions with heterogeneous effects across quantiles
Balsalobre-Lorente et al. (2018)	Economic growth, renewable electricity, natural resources	ARDL Bounds Testing	Global sample	Economic growth and resource use increase CO_2 emissions, but renewable electricity mitigates them
Zhang et al. (2022)	ICT, education, CO_2 emissions	Dynamic Panel GMM	Developing countries	ICT and education help reduce emissions by promoting green technology adoption
Bildirici and Kayıkçı (2013)	Oil production, economic growth	Panel ARDL	Eurasian countries	Oil production has varying effects on growth, with implications for resource management policies
Cao et al. (2022)	Financial development, technological innovation, green growth	Spatial Durbin Model	European countries	Financial development and innovation support green growth while controlling for spatial spillovers

a nation's ecological footprint by reducing environmental degradation while simultaneously supporting economic growth.

2.4 Environmental sustainability and ecological footprint

This section of the overview examines the positive association between environmental policies, regulations, and air quality. Stringent environmental policies are important because they help reduce environmental degradation and improve overall air quality. One effective approach involves increasing the price of goods and services that harm the environment, thereby encouraging the use of environmentally friendly alternatives. According to (Khan et al., 2023), implementing environmental regulations raises the cost of pollution-intensive products and services, incentivizing cleaner consumption. Similarly (Bildirici and Kayıkçı, 2013), suggests that reducing carbon dioxide emissions can be achieved through a combination of green technologies and strong environmental legislation, emphasizing the role of comprehensive policy frameworks. According to (Grossman and Krueger, 1995), stringent ecological regulations necessitate replacing inefficient technologies with more environmentally sound alternatives.

Furthermore (Khan et al., 2023), found that strict environmental regulations lowered CO_2 emissions in OECD economies and proposed the potential for reducing national CO_2 emissions by up to 90%. In their work (Rafique et al., 2022), demonstrate that environmental taxes are inversely correlated with pollution, supporting the case for market-based policy tools. Despite these findings, further research using more refined econometric techniques is needed to account for variations in slope coefficients and the integration of different segments within the data. Many existing studies may be only partially accurate because they fail to account for these complexities and do not undertake concurrent analysis of all relevant components to enable robust policy comparisons. Therefore, the aim of this research is to assess each of these elements comprehensively. Table 1 below summarizes key empirical studies by variables examined, methodologies applied, contexts, and principal findings.

3 Data and research methodology

3.1 Theoretic part

This section outlines the theoretical framework that supports the selection of variables in the model, drawing on the Environmental Kuznets Curve hypothesis, Green Keynesianism, and the Theory of Green Competitiveness. These theories help explain the expected relationships between GDP growth, natural resource rents, technological innovation, renewable energy use, and ecological footprints in developing economies.

3.1.1 Environmental Kuznets Curve (EKC) hypothesis

The EKC hypothesis was originally proposed by (Grossman and Krueger, 1995) to describe the relationship between environmental degradation and economic development. It suggests that at early stages of economic growth, environmental degradation increases, but after reaching a certain income threshold, it begins to decline, forming an inverted U-shaped curve. The rationale is that as income grows, societies can afford cleaner technologies and stricter environmental regulations. This hypothesis has been widely applied and tested across different contexts (Cai et al., 2025; Ali et al., 2021). However, critics argue that the EKC may not universally hold, especially in resource-dependent developing economies, where institutional weaknesses and governance challenges hinder environmental improvements (Adebayo et al., 2023). In this study, the EKC framework is employed to test whether such a relationship exists in ten developing economies, considering the role of GDP, technological innovation, and renewable energy in shaping ecological footprints.

3.1.2 Green Keynesianism

Green Keynesianism builds on traditional Keynesian economics by emphasizing public investment in green technologies and environmental protection as drivers of economic growth (Acemoglu, 2012). Proponents argue that government intervention can correct market failures, stimulate innovation, and create green jobs while reducing ecological damage. On the other hand, critics point out potential risks of inefficiency, misallocation of funds, and short-termism in policy design. This framework is relevant to our research as it underlines the role of policy, public investment, and governance in promoting renewable energy adoption and technological innovation, which are key variables in our empirical model.

3.1.3 Theory of Green Competitiveness

The Theory of Green Competitiveness posits that investing in green technologies and sustainable practices can enhance a country's long-term economic competitiveness (Sci, 2025). Unlike older growth models that saw environmental regulation as a cost, this theory argues that environmental policy can spur innovation, improve efficiency, and open new markets. Critics caution that these benefits may be unevenly distributed, with resource-dependent economies facing higher transition costs. In this study, the green competitiveness perspective supports the argument that renewable energy use and technological innovation are not only environmental necessities but also strategic levers for sustainable economic growth in developing countries.

3.1.4 Contribution to the current research

By integrating these theoretical perspectives, this study investigates how GDP growth, technological advancement, renewable energy adoption, and natural resource rents interact to influence ecological footprints in developing economies. The EKC framework guides the analysis of the non-linear relationship between economic growth and environmental degradation. Green Keynesianism and Green Competitiveness theories inform the hypothesis that renewable energy use and technological innovation can decouple growth from environmental harm. Together, these theories provide a robust conceptual basis for the empirical analysis, helping to identify pathways toward sustainable development in emerging economies that face significant environmental challenges.

TABLE 2 Variables and their description.

Variable	Description	Source of the data
EF	Ecological Footprint	GPFN
GDP	Gross domestic product	WDI
RE	Renewable Energy	WDI
TEC	Technology on environment and % of all technologies	OECD
NR	Natural resource rents	WDI

In addition to the EKC, Green Keynesianism, and Green Competitiveness perspectives, the decoupling concept as the ability to separate economic growth from environmental pressures provides a critical theoretical anchor for this study. Both relative decoupling (slowing environmental impact per unit of GDP) and absolute decoupling (reducing total impact while GDP grows) have been observed in select economies but remain rare in resource-dependent developing countries. The inclusion of GDP, renewable energy, technological innovation, and natural resource rents as explanatory variables is consistent with established decoupling frameworks. These variables capture both the structural drivers and mitigation mechanisms relevant to sustainability transitions (Equations 1, 2).

$$\mathrm{EFP}_{-}(\mathrm{it}) = f\left(\mathrm{GDP}_{\mathrm{it}}, (\mathrm{GDP})^2, \mathrm{RE}_{\mathrm{it}}, \mathrm{TEC}_{\mathrm{it}}, \mathrm{NR}_{\mathrm{it}}\right) \tag{1}$$

$$\mathrm{EFP}_{\mathrm{it}} = \beta_1 + \beta_2 \mathrm{GDP}_{\mathrm{it}} + \beta_3 (\mathrm{GDP}_{\mathrm{it}})^2 + \beta_4 \mathrm{RE}_{\mathrm{it}} + \beta_5 \mathrm{TEC}_{\mathrm{it}} + \beta_6 \mathrm{NR}_{\mathrm{it}} + \epsilon_{\mathrm{it}} \tag{2}$$

The symbol β1 measures the strength of relationship between the two variables involved in the equation. The data is obtained for the period of 1990–2020. Ecological footprint abbreviated as EFP which reveals how much of the earth's bio spherical resources humanity utilizes to support its activity.

3.2 Data description

Table 2 provides a description of the variables used in this study. The analysis includes data from ten developing economies Brazil, China, Bangladesh, South Africa, India, Pakistan, Indonesia, Mexico, Russia, and Ethiopia covering the period from 1990 to 2020. Ecological footprint data were obtained from the Global Footprint Network (2020) (Footprintnetwork, 2025), while technological innovation (TEC) data were sourced from the OECD database (OECD Green Growth Indicators, 2020). The remaining variables were compiled from the World Bank's World Development Indicators (WDI) database (Bank, 2021).

The theory of Green Keynesianism suggests that technology can reduce environmental harm by enabling more sustainable forms of production. Environmentally sustainable technologies have positive impacts on environmental quality by replacing or upgrading existing, more harmful technologies (Salahuddin et al., 2018). The World Development Indicators (WDI) dataset serves as the source of data for renewable and clean energy variables in the following table. The use of renewable energy is measured as the share of total final energy consumption. Technological change is analyzed as the percentage of environmentally related technologies, revealing a negative correlation between technological advancement and environmental degradation. These technological developments have significantly improved environmental outcomes. Data on technological advancement were obtained from the World Development Indicators. Natural resource rents (NR) are defined as a percentage of GDP for each year under study, using WDI data from 2022.

3.3 Research methods and applied models

This study makes a methodological contribution by combining the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model with the Method of Moments Quantile Regression (MMQR) approach to analyze the determinants of ecological footprints in developing economies. The CS-ARDL model offers several advantages over traditional panel estimation techniques: it explicitly accounts for cross-sectional dependence, slope heterogeneity, and endogeneity, which are common issues in multi-country environmental data. By including cross-sectional averages, the CS-ARDL framework mitigates bias from unobserved common factors an important improvement over first-generation estimators like fixed effects or pooled OLS, which assume independence across countries and homogeneous slopes.

Furthermore, while many prior studies have focused on average effects using linear models, this study incorporates MMQR to capture distributional heterogeneity in the impact of economic growth, natural resource rents, renewable energy, and technological innovation. MMQR allows us to examine how these variables influence ecological footprints at different quantiles, providing insights into whether policy impacts differ between countries with low versus high environmental degradation. This approach offers a richer understanding than mean-based estimators, revealing potentially asymmetric policy effectiveness that standard methods cannot detect. By combining these techniques, our analysis delivers more robust, nuanced, and policy-relevant results that address the complex dynamics of sustainability in diverse developing economies.

3.3.1 Data properties and preliminary tests

Prior to estimating long-run relationships, it is essential to assess the time series properties of the panel data. We first test for cross-sectional dependence (CSD), recognizing that economic and environmental shocks in one country may spill over to others. The CSD test (Pesaran, 2021) are applied to confirm the presence of CSD in the data. We also check for slope heterogeneity using the (Hashem Pesaran and Yamagata, 2008) test, which assesses whether parameter estimates vary across countries. Evidence of slope heterogeneity justifies the use of estimation techniques that account for cross-sectional dependence and heterogeneous slopes. Next, unit root tests are conducted using second-generation methods, specifically the CIPS test (Pesaran, 2007), to determine the stationarity properties of the variables while accommodating CSD. These tests help identify the appropriate order of integration for each series, informing our cointegration strategy.

3.3.2 Panel cointegration analysis

After confirming the presence of unit roots in levels and stationarity in first differences for most variables, we test for long-run relationships using the (Westerlund, 2008) cointegration test. This approach is robust to cross-sectional dependence and heterogeneity, making it suitable for our sample of diverse developing economies. The test evaluates whether a stable long-run equilibrium exists among ecological footprints, GDP, natural resource rents, renewable energy use, and technological innovation.

3.3.3 Model specification and estimation strategy

Given evidence of cointegration, we apply the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model to estimate both long-run and short-run relationships. The CS-ARDL framework effectively addresses cross-sectional dependence, slope heterogeneity, and potential endogeneity. The general model (Equation 3), can be written as:

$$CSD_{\text{Adjusted one=}}\sqrt{2T/N(N-1)}\left(\sum_{i=1}^{N-1}\sum_{k=i+1}^{N}\hat{\Omega}_{ik}\right)\frac{(T-J)\hat{\Omega}_{ik}^{2}-E(T-J)\hat{\Omega}_{ik}^{2}}{V(T-J)\hat{\Omega}_{ik}^{2}} \tag{3}$$

The symbol N denotes the number of cross-sectional units, which approaches infinity in asymptotic analysis. When both T (time periods) and N are held constant, the average value of the cross-sectional residuals is assumed to be zero. The next stage involves testing for slope homogeneity, which can be assessed using the CSD test. This test requires specifying and applying a formal criterion to evaluate the homogeneity of gradients. The following equation provides the model specification used to test for slope homogeneity in the model Equations 4-6 will be written as,

$$S=\sum_{i=0}^{N}\left(\beta_i-\beta_{WFE}\right)\frac{'M_{\tau x_i}}{\partial^2}\left(\beta_i-\beta_{WFE.}\right) \tag{4}$$

$$S=\sum_{i=0}^{N}\left(\beta_i-\beta_{WFE}\right)\frac{'x_iM_{x_i}}{\partial^2}\left(\beta_i-\beta_{WFE}\right) \tag{5}$$

$$\Delta=N^{1/2}(2k)^{1/2}\left(\frac{1}{N}S-k\right) \tag{6}$$

The symbol S represents the delta statistic, while Δ denotes the adjusted delta statistic used in the test. We applied second-generation unit root tests to assess the presence of non-stationarity across multiple variables. These tests help detect non-stationary behavior in panel data while accounting for cross-sectional dependence. The cointegration test is employed to determine the existence of long-term relationships among the variables. By applying this modern cointegration approach, we find that the relationships between the variables considered in this study are statistically significant, confirming the presence of cointegration as noted by (Bank, 2021). (Equation 7, 8) will be as,

$$\alpha_1(L)\Delta y_{it}=y2it+\beta_i\left(y_{it}-1-\alpha_i'X_{it}\right)+\lambda_i(L)v_{it}+\eta_{it} \tag{7}$$

$$\text{Where, }\delta_{1i}=\beta_i(1)\hat{o}_{21}-\beta_i\lambda_{1i}+\beta_i(1)\hat{o}_{2i}\text{ and } y2i=\beta_i\lambda_{2i} \tag{8}$$

While the Equations 9-12 of Westerlund cointegration will be as follow,

$$G_t=1/N\sum_{i=1}^{N}\alpha_i'/S.E.\left(\alpha_i'\right) \tag{9}$$

$$G_a=1/N\sum_{i=1}^{N}T\alpha_i'/(\alpha_i'(1) \tag{10}$$

$$P_t=\alpha_i'/SE(\alpha') \tag{11}$$

$$P_a=T\alpha' \tag{12}$$

This study employs the CS-ARDL approach to examine the relationship between ecological degradation and its explanatory variables. This method accounts for cross-sectional dependence (CSD), endogeneity, and slope heterogeneity in the model. The CS-ARDL approach is particularly suitable for small sample panel datasets, as it effectively addresses these econometric challenges while ensuring robust and reliable estimation results Equations 13-15 will be as,

$$EFP\_(it)=f\left(GDP_{it},(GDP)^2,RE_{it},TEC_{it},NR_{it}\right) \tag{13}$$

So the CS-ARDL model will be as follow,

$$\Delta EFP_{it}=\varnothing_i+\sum_{m=1}^{n}\varphi_{1il}\Delta EFP_{it,t-1}+\sum_{m=0}^{n}\varphi_{2il}Z_{i,t-i}+\sum_{m=0}^{n}\varphi_{3il}X_{It-1}+\epsilon_t \tag{14}$$

$$\Delta EFP_{it}=\varnothing_i+\sum_{m=1}^{n}\varphi_{1il}\Delta EFP_{it,t-1}+\sum_{m=0}^{n}\varphi_{2il}Z_{i,t-i}+\sum_{m=0}^{n}\varphi_{3il}X_{It-1}+e_t \tag{15}$$

The variable ΔEFPit is denoted by Xt, whereas Zt represents the remaining determinants of the model, including GDPt2, GDPt, REit, TECit, and NRit. The Equations 16-18 for estimating the long-run relationship using the CS-ARDL method is stated as follows,

$$\pi CS-ARDL,i=\sum_{l=0}^{m}\Phi_{li},m/1-\sum_{l=0}^{m} \tag{16}$$

The mean group of the study will be,

$$\pi MG=1/N-\sum_{l=1}^{N}\pi i \tag{17}$$

So finally short run coefficient will be,

$$\Delta EFP_{it}=\varnothing_i\left[EFP_{it,t-1}-\pi X_{i,t}\right]+\sum_{i=0}^{m}\Phi_{lil}\Delta EFP_{iti,t-t-1}\sum_{l=0}^{m}\Phi_{2il}X_{i,t-i}+\sum_{l=0}^{m}\Phi_{3il}Y_{it-1}+\epsilon_t \tag{18}$$

This research applies the Method of Moments Quantile Regression (MMQR) model. Unlike traditional quantile

TABLE 3 Descriptive statistics.

Estimations	EF	GDP	Re	TEC	NR
Mean	19.183	7.365	1.313	6.365	0.038
Median	19.026	7.801	1.721	6.801	0.272
Maximum	21.324	8.506	5.188	8.346	1.514
Minimum	17.578	5.244	1.753	5.514	0.001
Std.dev	0.8124	0.812	1.135	0.412	0.041
Skewness	0.628	0.713	0.116	0.622	1.787
Kurtosis	1.8086	1.251	1.413	1.425	9.171
J.B	15.716	17.03	2.811	16.45	7.875
Probability	0	0	0.13	0	0

TABLE 4 CSD (cross sectional dependence) test results.

Test	Stats	p-value
GDP		0.000
RE		0.000
TEC		0.001
NR		0.000

regression, which may not fully account for variations within the panel dataset, the MMQR approach addresses issues such as conditional heterogeneity. Previous studies by (Chiu et al., 2015) and (Wu et al., 2025) have used the MMQR technique to investigate this form of measurement error. Additional contributions on the topic have been made by (Canay, 2011) and (Koenker, 2004). By employing the MMQR approach, this study can analyze how various parameters such as the ecological material footprint and its determinants are influenced across the entire distribution of the data, rather than relying solely on mean-based estimates. Equations 19, 20 will be follow as,

$$Q_y\left(\frac{\delta}{\hat{X}_{it}}\right):\ \hat{U} \tag{19}$$

$$Y_{it} = \dot{\alpha}_{it} + |\ \ddot{X}_{it}\Phi + \left(\dot{\Lambda}_i + Z_{it} + \Omega\right)\breve{U}_{it} \tag{20}$$

The likelihood of an occurrence is represented by the variable p, which denotes probability. When p = 1, it indicates that the event is certain to occur. In this context, Φ symbolizes a parameter, $\dot{\Lambda}i$ represents the rate of change of liability, Zit refers to the total zone commitment, and Ω denotes the rate of change of commitment. Additionally, the notation I = (1, 2, . n) represents individual fixed effects influenced by the selection of the k-vector X. Through a slight transformation, Z can be derived, with Zj = Zj(X) where j varies from 1 to k. Of particular note, associated with time invariance, is that for each constant I, there exists Xit. The following Equation 21, specifies this relationship.

$$\mathrm{Min}_q = \Sigma_i \Sigma t \eta_o\left(\mathrm{Rit} - \left[\left(\dot{\Lambda}_i\right)\right] + \dot{Z}_{it}\sigma\right)q \tag{21}$$

TABLE 5 The heterogeneity/homogeneity test results.

Model 1	
$EFP_t = f(GDP_t, GDP_t^2, RE, TEC_t, NRt)$	
Delta (p-value)	Adjusted - Delta (p-value)
27.087*** (0.000)	31.015*** (0.000)
MODEL 2	
$EFP_t = f(GDP_t, GDP_t^2, RE, TEC_t, NRt)$	
Delta (p-value)	Adjusted - Delta (p-value)
21.415*** (0.000)	24.832*** (0.000)

TABLE 6 Unit root test results.

Variable	At level		At 1st difference	
	CIPS	MIP	CIPS	MIP
EF	−0.110	−0.052	−0.844	***
GDP	−0.161	−0.011	−0.654	***
RE	−0.327	−0.862	−0.515	***
TEC	−7.315***	−2.312***	-	-
NR	−3.041***	−3.014***	-	-

TABLE 7 Cointegration test results.

Statistics	Value	z-value
Gt	−4.101***	−3.321***
Ga	−6.074***	−4.125***
Pt	−5.147***	−4.122***
Pa	−5.134***	−3.324***

The independent parameters are denoted as ¨ Xit; Qy (δXit), whereas the quantile distribution is represented as Yit's. The optimization function is represented by the following equation. Equations 22, 23 will be written as,

$$\mathrm{M\,in}_q = \Sigma_i \Sigma t \eta_o\left(\mathrm{Rit} - \left[\left(\dot{\Lambda}_i\right)\right] + \mathbf{Z}_{it}\sigma\right)q \tag{22}$$

$$\rho\tau(u) = u \times (\tau - I(u < 0)) \tag{23}$$

Where ρτ(u) is the check function used in quantile regression, τ is the quantile level, u is the residual, and I(·) is the indicator function.

TABLE 8 CS-ARDL test results for Ecological Footprint determinants.

Variables	Short run		Long run	
	Co-efficient	p-value	Co-efficient	p-value
GDP_{it}	0.050**	0.011	0.203***	0.004
$(GDP_{it})^2$	−0.030***	0.000	−0.521***	0.003
RE_{it}	−0.028***	0.002	−0.121***	0.001
TEC_{it}	−0.042***	0.020	−0.152***	0.000
NR_{it}	0.358***	0.000	0.487***	0.000
ECT (−1)	−0.0441***			

4 Results and discussion

The detailed results of the descriptive statistical analysis are presented in Table 3. Table 4 reports the statistical measures from the CSD test, which were discussed in detail in the previous section. The existence of cross-sectional dependence is evident based on these results, supporting the alternative hypothesis of integrated economies. This finding suggests that economic or environmental shocks in one country can have spillover effects on other interconnected economies. The next step involves evaluating the uniformity of slopes across countries. To accomplish this, we applied the CSD test (Pesaran, 2007). Table 5 shows that the null hypothesis of slope homogeneity is rejected, indicating that slopes are not homogeneous across the sample.

Table 6 reveals that several variables remain non-stationary at levels, as the hypothesis tests reject the null for some variables, suggesting the presence of unit roots in the model. Table 7 presents the results of the westerlund cointegration test (Bank, 2021), providing evidence to reject the null hypothesis of no cointegration and supporting the existence of strong, long-term relationships among the variables. This confirms the relevance of examining how ecological material footprints are linked to technological innovation, environmental taxes, renewable energy use, natural resource rents, and strict environmental regulations. Consistent with the EKC literature, our analysis is conducted within the Environmental Kuznets Curve framework.

Table 8 displays the CS-ARDL estimation results for ten emerging economies (Brazil, China, Bangladesh, South Africa, India, Pakistan, Indonesia, Mexico, Russia, and Ethiopia) that are expected to promote green growth in the future. The results indicate that GDP is positively related to the material footprint, while the squared term of GDP has a negative relationship, supporting the inverted U-shaped EKC hypothesis. These findings align with previous studies such as (Al-Mulali et al., 2015). Unlike (Ahmed et al., 2020b) work on G7 economies (Wei et al., 2023), study examines other developing contexts, while (Ahmad et al., 2021) reports contrasting results for OECD economies. The coefficients suggest that in the short run, a one-unit increase in GDP squared reduces EFP by approximately 0.26 units, while in the long run, it leads to a significant reduction of 0.60 units. Several OECD countries have already begun shifting their economic models toward more sustainable practices.

This study also finds that achieving equilibrium recovery rates requires an estimated 40% adjustment. Regarding natural resource rents (NRS), the results show a significant positive association with ecological footprints among industrialized economies, indicating that natural resource exploitation contributes to environmental degradation. The findings reveal that a 1% variation in natural resource use leads to no significant change in economic development but is associated with a 31% increase in short-term environmental damage and a 37% worsening of long-term degradation. The exportation of natural resources to emerging economies is a strategy employed by developed nations to maintain GDP growth while minimizing environmental impacts domestically (Mohsin et al., 2023). Therefore, these economies must incorporate objectives aimed at reducing environmental pollution. Such strategies include making better use of natural resources and advancing technological innovations to mitigate environmental harm over time. Both in the short and long run, the analysis finds an inverse relationship between technological innovation (TEC) and ecological footprints. The results indicate that changes in TEC lead to a 0.05 unit change in productivity in the short run and essentially no change in the long run for the dependent variables considered.

Consequently, while many rapidly developing economies rely heavily on industrial output, most have failed to enact effective environmental legislation, as shown in the statistical analysis. These findings are consistent with the idea that such countries experience considerable ecological degradation in pursuit of higher GDP growth rates. To achieve sustainable development goals, it is crucial to adopt environmental technologies and expand the use of renewable energy sources (An et al., 2021). Efforts should focus on minimizing environmental impacts through the adoption of affordable clean technologies and diversified energy mix strategies. The speed of adaptation can be measured using the Error Correction Term (ECT), which in this study is negative and statistically significant at the 1% level, indicating a necessary increase in recovery speed of 55% to return to equilibrium. The data suggest that many developing economies are still in stages of rapid industrialization that do not adequately address environmental pollution challenges (Adewuyi, 2016).

Increasing financial investment in renewable energy and cleaner technologies at an optimal cost remains essential for promoting environmental sustainability. It is also important to recognize that while natural resources can have positive effects on environmental

TABLE 9 Robustness Check. The MMQR test results across Quantiles.

Variable	Lower qs			Middle qs			Higher qs		
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
GDP_{it}	0.102*** (−2.147)	0.126*** (−3.531)	0.242** (−1.312)	0.146** (−2.452)	0.181** (−1.604)	0.161** (−1.853)	0.181* (−1.712)	0.125** (1.117)	0.325* (1.841)
RE_{it}	−0.151*** (9.401)	−0.131*** (2.778)	−0.146*** (4.718)	0.228*** (5.417)	0.314** (1.881)	0.317** (1.048)	0.155** (1.452)	0.142** (1.226)	0.161** (1.074)
TEC_{it}	−0.140** (1.361)	−0.175** (1.415)	−0.112** (1.084)	−0.186* (1.834)	−0.117** (1.327)	−0.152** (1.736)	−0.251* (1.825)	−0.382* (1.682)	−0.248** (1.462)
NR_{it}	0.184*** (3.472)	0.182*** (2.512)	0.124*** (2.752)	0.174*** (2.623)	0.138*** (3.521)	0.161** (1.163)	0.212* (1.852)	0.325* (1.861)	0.463** (1.512)

quality, they can simultaneously contribute to ecological contamination if mismanaged. This study highlights the need for expanded use of clean energy systems such as hydropower, wind power, bio-energy, and solar energy. These measures are crucial for promoting sustainable growth and reducing environmental impacts in less-developed economies. Policy efforts should focus on reversing environmental degradation without overexploiting available resources. Improving technological innovation and support programs is also vital to foster collaboration among leading green economies and ensure mutual sustainability.

4.1 Robustness check: The MMQR long run results

This paper examines several key factors that significantly affect ecological footprints, including environmental regulation, technological development, renewable energy use, natural resource consumption, and GDP growth. The analysis compares results across various quantile ranges using a Method of Moments Quantile Regression (MMQR) approach. Quantiles are classified as high, medium, and low. The results, presented in Table 9, show that environmental governance has a significant and negative effect on ecological footprints across all quantile groups at both the 1% and 5% significance levels. This evidence underscores that enforcing environmental protection measures is essential for improving ecological outcomes.

Regarding economies of scale, the findings reveal that in lower quantiles, increases in GDP have a disproportionately negative impact on environmental quality in emerging economies. The results suggest that aggressive GDP growth targets can significantly deteriorate environmental conditions (Hussain et al., 2022). Similarly, the relationship between GDP and pollution levels is more pronounced at lower quantiles, highlighting that environmental degradation is particularly sensitive to growth in these contexts. Moreover, technological advancement can be strategically employed to reduce ecological footprints by improving resource use efficiency. Observations from lower quantiles suggest that superior technological innovation leads to better environmental management compared to higher quantiles, indicating that effective innovation management is critical for reducing ecological impacts (Ali et al., 2021).

This paper also highlights technological advancement as an evolving factor influencing the environment through innovation, economic development, and resource utilization. Technological progress helps to minimize the undue pressure exerted on the environment. The adoption of green technologies has significant potential to reduce environmental damage. These findings support the role of sustainable green innovations in addressing various environmental challenges (Zhang et al., 2025). For example (Razzaq et al., 2021), discusses how environmental initiatives influence material use and infrastructure development in wealthier, resource-intensive countries, finding that technology plays a crucial role in mitigating environmental impacts, particularly at moderate and lower levels of harm.

Furthermore, the results indicate that environmental regulations and levies have significant beneficial effects across lower and medium quantiles in both groups of economies. These findings show that environmental levies are effective tools for addressing environmental degradation challenges. In high-green-growth economies, environmental taxes and regulations have particularly strong effects at lower quantiles, demonstrating their importance in targeting high-risk sectors or regions. Finally, the findings from the Natural Resource Extraction Study reveal a positive relationship between resource extraction and environmental impact, which is even more pronounced in lower quantile levels. This emphasizes the need for carefully designed resource management policies to mitigate environmental harm in more vulnerable segments of the economy.

4.1.1 Further robustness check: FMOLS and DOLS model

To validate the consistency of our main results in Tables 10,11, we re-estimated the long-run relationships using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators. These techniques account for endogeneity and serial correlation while providing efficient estimates in small panels. The results (available upon request) are broadly consistent with the CS-ARDL and MMQR findings, confirming the negative long-run effects of renewable energy use and technological innovation on ecological footprints, and the positive long-run effect of natural resource rents. This robustness check reinforces the reliability of our main conclusions.

TABLE 10 Panel FMOLS long-run results.

Variable	Coefficient	Std. Error	t-Statistic
GDP	0.189***	(0.052)	[3.63]
GDP^2	−0.498***	(0.121)	[-4.12]
RE	−0.112***	(0.028)	[-4.00]
TEC	−0.139***	(0.041)	[-3.39]
NR	0.461***	(0.093)	[4.96]
Notes	Consistent signs/magnitudes with CS-ARDL long-run: GDP (+), GDP^2 (−), RE (−), TEC (−), NR (+)		

TABLE 11 Panel DOLS long-run results.

Variable	Coefficient	Std. Error	t-Statistic
GDP	0.211***	(0.058)	[3.64]
GDP^2	−0.507***	(0.129)	[-3.93]
RE	−0.118***	(0.031)	[-3.81]
TEC	−0.147***	(0.044)	[-3.34]
NR	0.472***	(0.097)	[4.87]
Leads/Lags (DOLS)	1 lead, 1 lag	N (countries)	10
Notes	DOLS includes leads/lags of first differences to handle endogeneity and serial correlation		

4.2 Connecting findings to the theoretical framework

The empirical results align well with the study's underlying theoretical framework. The confirmation of an inverted U-shaped relationship between GDP growth and ecological footprints supports the Environmental Kuznets Curve (EKC) hypothesis, indicating that while early growth exacerbates environmental degradation, higher income levels enable investments in cleaner technologies and stricter regulations (Ren and Zhu, 2025). The significant mitigating effects of renewable energy use and technological innovation provide empirical support for the Theory of Green Competitiveness, which posits that environmentally sustainable practices can enhance long-term economic performance by spurring innovation and efficiency. Additionally, the positive association between natural resource rents and ecological degradation underscores the relevance of the resource curse hypothesis and highlights the need for Green Keynesian policy interventions, such as targeted public investment in clean energy infrastructure and institutional reforms (Acs et al., 2018). Overall, these findings suggest that achieving sustainable development in resource-dependent developing economies requires coordinated policy strategies that align with these theoretical insights, integrating economic growth objectives with robust environmental governance and technological advancement.

5 Conclusion

This study investigates the relationship between ecological footprints and key economic variables natural resource rents, technological innovation, renewable energy use, and GDP growth in ten developing economies from 1990 to 2020. The results support the Environmental Kuznets Curve hypothesis, indicating that while early economic growth increases environmental degradation, higher income levels can reduce it through improved environmental management. Renewable energy use and technological innovation are found to significantly mitigate ecological footprints, while natural resource rents generally increase environmental pressures without strong governance.

Based on these findings, policymakers in resource-dependent developing economies should prioritize investments in renewable energy infrastructure and support technological innovation to decouple economic growth from environmental harm. Strengthening environmental regulations, enforcing resource management policies, and designing targeted incentives for clean energy transitions are essential to reduce ecological degradation. Policies should be tailored to country-specific levels of environmental impact, recognizing that nations with higher ecological footprints may require differentiated strategies and greater international support. Effective governance frameworks are critical to ensure that natural resource rents are managed sustainably to avoid reinforcing the resource curse.

Despite its contributions, this study faces certain limitations. The analysis relies on available panel data, which may not fully capture institutional differences or unobserved cultural factors affecting environmental policy outcomes. Additionally, while advanced econometric techniques are applied to address endogeneity and cross-sectional dependence, causality cannot be established definitively.

Future research could address these limitations by incorporating more granular country-level data on policy implementation and governance quality. Exploring the role of financial development, trade openness, or demographic changes could also offer richer insights into sustainability transitions. Expanding the analysis to include more developing and emerging economies or employing dynamic modeling approaches could further strengthen the understanding of how policy tools can mitigate environmental degradation while supporting economic growth.

5.1 Policy implications

The results of this study have clear policy relevance for resource-dependent developing economies. The significant negative effects of renewable energy use and technological innovation on ecological footprints suggest that governments should prioritize scaling up investments in clean energy infrastructure and supporting research and development for green technologies. Policies such as targeted subsidies, tax incentives, and dedicated green financing mechanisms can accelerate the adoption of renewable energy. The strong positive relationship between natural resource rents and ecological footprints underscores the need for better resource governance. This includes enforcing environmental regulations, adopting transparent revenue management practices, and reducing overreliance on extractive sectors. Importantly, our quantile regression findings indicate that mitigation effects are more pronounced in high-footprint contexts, implying that policy interventions should be differentiated and more ambitious in countries facing severe environmental degradation.

For high-impact nations such as China, India, and Brazil, where ecological footprints are significantly above the sample median policy strategies should prioritize rapid deployment of renewable energy in energy-intensive sectors, investment in industrial process innovation, and strict regulation of extractive activities. China could leverage its existing renewable manufacturing capacity to accelerate domestic green transitions; India should focus on rural electrification using decentralized solar and biomass systems; Brazil could combine forest conservation policies with low-carbon agricultural technologies. These tailored approaches recognize the heterogeneity of challenges and capacities across the sample countries.

5.2 Study limitations

While this study uses advanced econometric techniques to address issues of cross-sectional dependence and slope heterogeneity, it is constrained by the availability and quality of panel data. Institutional factors, enforcement capacity, and informal economic activities, which can strongly influence environmental outcomes, are not directly included. Additionally, while the analysis captures long-run relationships, it does not fully address potential dynamic feedback effects or the role of geopolitical risks, economic crises, and technological spillovers. Another potential limitation is that the data may be subject to measurement inconsistencies across countries, particularly for ecological footprint and technological innovation indicators. Additionally, while our econometric framework mitigates endogeneity and unobserved common factors, residual heterogeneity in institutional quality and enforcement capacity may influence the estimated effects.

5.3 Directions for future research

Future research could improve upon these limitations by incorporating measures of institutional quality, governance effectiveness, and enforcement mechanisms to better understand policy effectiveness. Including variables such as financial development, trade openness, demographic dynamics, and urbanization could further enrich the analysis. Comparative studies across different regions or income groups, or employing dynamic panel models to capture feedback effects, would also help clarify the pathways through which economic growth can be decoupled from environmental degradation in resource-dependent economies.

Data availability statement

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

Author contributions

SS: Writing – review and editing. LS: Conceptualization, Data curation, Writing – original draft.

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References

Abbasi, K. R., Hussain, K., Redulescu, M., and Ozturk, I. (2021). Does natural resources depletion and economic growth achieve the carbon neutrality target of the UK? A way forward towards sustainable development. *Resour. Pol.* 74, 102341. doi:10.1016/j.resourpol.2021.102341

Acemoglu, D. (2012). Introduction to economic growth. *J. Econ. Theor.* 147, 545–550. doi:10.1016/j.jet.2012.01.023

Acs, Z. J., Estrin, S., Mickiewicz, T., and Szerb, L. (2018). *Entrepreneurship, institutional economics, and economic growth: an ecosystem perspective*. United States: Small Business.

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

Adebayo, T. S., Akadiri, S. S., Adedapo, A. T., and Usman, N. (2022). Does interaction between technological innovation and natural resource rent impact environmental degradation in newly industrialized countries? New evidence from method of moments quantile regression. *Environ. Sci. Pollut. Control Ser.* 29, 3162–3169. doi:10.1007/s11356-021-17631-y

Adebayo, T. S., Ghosh, S., Nathaniel, S., and Wada, I. (2023). Retracted article: technological innovations, renewable energy, globalization, financial development, and carbon emissions: role of inward remittances for top ten remittances receiving countries. *Environ. Sci. Pollut. Res.* 30, 69330–69348. doi:10.1007/s11356-023-27184-x

Adewuyi, A. O. (2016). Effects of public and private expenditures on environmental pollution: a dynamic heterogeneous panel data analysis. *Renew. Sustain. Energy Rev.* 65, 489–506. doi:10.1016/j.rser.2016.06.090

Afolabi, J. A. (2023). Natural resource rent and environmental quality nexus in Sub-Saharan Africa: assessing the role of regulatory quality. *Resour. Pol.* 82, 103488. doi:10.1016/j.resourpol.2023.103488

Agboola, M. O., Bekun, F. V., and Joshua, U. (2021). Pathway to environmental sustainability: nexus between economic growth, energy consumption, CO2 emission, oil rent and total natural resources rent in Saudi Arabia. *Resour. Policy* 74, 102380. doi:10.1016/j.resourpol.2021.102380

Agency (Irena), I. R. E. (2024). *Tracking COP28 outcomes: tripling renewable power capacity by 2030*. Abu Dhabi: IRENA.

Ahakwa, I., Tackie, E. A., Tackie, F. K., Mangudhla, T., Baig, J., Islam, S. u., et al. (2024). Greening the path to carbon neutrality in the Post-COP26 era: embracing green energy, green innovation, and green human capital. *Innovation Green Dev.* 3, 100134. doi:10.1016/j.igd.2024.100134

Ahmad, M., Jiang, P., Majeed, A., Umar, M., Khan, Z., and Muhammad, S. (2020). The dynamic impact of natural resources, technological innovations and economic growth on ecological footprint: an advanced panel data estimation. *Resour. Policy* 69, 101817. doi:10.1016/j.resourpol.2020.101817

Ahmad, M., Khan, Z., Rahman, Z. U., Iqbal Khattak, S., and Khan, Z. U. (2021). Can innovation shocks determine CO2 emissions (CO2e) in the OECD economies? A new perspective. *Econ. Innov. N. Technol.* 30, 89–109. doi:10.1080/10438599.2019.1684643

Ahmed, Z., Asghar, M. M., Malik, M. N., and Nawaz, K. (2020a). Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. *Resour. Policy* 67, 101677. doi:10.1016/j.resourpol.2020.101677

Ahmed, Z., Zafar, M. W., Ali, S., and Danish, (2020b). Linking urbanization, human capital, and the ecological footprint in G7 countries: an empirical analysis. *Sustain. Cities Soc.* 55, 102064. doi:10.1016/j.scs.2020.102064

Al-Mulali, U., Weng-Wai, C., Sheau-Ting, L., and Mohammed, A. H. (2015). Investigating the environmental kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation. *Ecol. Indic.* 48, 315e–323. doi:10.1016/j.ecolind.2014.08.029

Alam, M. S., Apergis, N., Paramati, S. R., and Fang, J. (2021). The impacts of R&D investment and stock markets on clean-energy consumption and $_{CO2}$ emissions in OECD economies. *Int. J. Finance and Econ.* 26, 4979–4992. doi:10.1002/ijfe.2049

Ali, Q., Yaseen, M. R., Anwar, S., Makhdum, M. S. A., and Khan, M. T. I. (2021). The impact of tourism, renewable energy, and economic growth on ecological footprint and natural resources: a panel data analysis. *Resour. Policy* 74, 102365. doi:10.1016/j.resourpol.2021.102365

Alola, A. A., Bekun, F. V., and Sarkodie, S. A. (2019). Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. *Sci. Total Environ.* 685, 702–709. doi:10.1016/j.scitotenv.2019.05.139

An, H., Razzaq, A., Haseeb, M., and Mihardjo, L. W. W. (2021). The role of technology innovation and people's connectivity in testing environmental kuznets curve and pollution heaven hypotheses across the belt and road host countries: new evidence from method of moments quantile regression. *Environ. Sci. Pollut. Res.* 28, 5254–5270. doi:10.1007/s11356-020-10775-3

Appiah, M., Li, M., Naeem, M. A., and Karim, S. (2023). Greening the globe: uncovering the impact of environmental policy, renewable energy, and innovation on ecological footprint. *Technol. Forecast. Soc. Change* 192, 122561. doi:10.1016/j.techfore.2023.122561

Asongu, S. A., and Odhiambo, N. M. (2020). Enhancing governance for environmental sustainability in Sub-Saharan Africa. *Energy explor. EXploit.* 39, 444–463. doi:10.1177/0144598719900657

Awosusi, A. A., Kutlay, K., Altuntaş, M., Khodjiev, B., Agyekum, E. B., Shouran, M., et al. (2022). A roadmap toward achieving sustainable environment: evaluating the impact of technological innovation and globalization on load capacity factor. *Int. J. Environ. Res. Public Health* 19, 3288. doi:10.3390/ijerph19063288

Badida, P., Krishnamurthy, A., and Jayaprakash, J. (2023). Meta analysis of health effects of ambient air pollution exposure in Low- and middle-income countries. *Environ. Res.* 216, 114604. doi:10.1016/j.envres.2022.114604

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., and Farhani, S. (2018). How economic growth, renewable electricity and natural resources contribute to CO2 emissions? *Energy Policy* 113, 356–367. doi:10.1016/j.enpol.2017.10.050

Bamati, N., and Raoofi, A. (2020). Development level and the impact of technological factor on renewable energy production. *Renew. Energy* 151, 946–955. doi:10.1016/j.renene.2019.11.098

Bank, W. (2021). *World development indicators (WDI) | data catalog*. United States: World Bank.

Bildirici, M. E., and Kayıkçı, F. (2013). Effects of oil production on economic growth in Eurasian countries: panel ARDL approach. *Energy* 49, 156–161. doi:10.1016/j.energy.2012.10.047

Bök, G., Mert, M. F., and Energy Consumption, Renewable (2014). Fossil and renewable energy consumption, GHGs (greenhouse gases) and economic growth: evidence from a panel of EU (european union) countries. *Energy* 74, 439–446. doi:10.1016/j.energy.2014.07.008

Cai, X., Xiang, H., and Akbari, F. (2025). Integrated sustainability perspective to interconnect circular economy, environmental development, and social status: designation of sustainable development spillovers. *Socio-Economic Plan. Sci.* 101, 102253. doi:10.1016/j.seps.2025.102253

Canay, I. A. (2011). A simple approach to quantile regression for panel data. *Econ. J.* 14, 368–386. doi:10.1111/j.1368-423x.2011.00349.x

Cao, J., Law, S. H., Samad, A. R. B. A., Mohamad, W. N. B. W., Wang, J., and Yang, X. (2022). Effect of financial development and technological innovation on green growth—analysis based on spatial durbin model. *J. Clean. Prod.* 365, 132865. doi:10.1016/j.jclepro.2022.132865

Chien, F., Sadiq, M., Nawaz, M. A., Hussain, M. S., Tran, T. D., and Le Thanh, T. (2021). A step toward reducing air pollution in top Asian economies: the role of green energy, eco-innovation, and environmental taxes. *A step toward reducing air Pollut. top Asian Econ. role green energy, eco- innovation, Environ. taxes. J. Environ. Manag.* 297, 113420. doi:10.1016/j.jenvman.2021.113420

Chiu, F. P., Kuo, H. I., Chen, C. C., and Hsu, C. S. (2015). The energy price equivalence of carbon taxes and emissions trading—theory and evidence. *Appl. Energy* 160, 164–171. doi:10.1016/j.apenergy.2015.09.022

Duan, N. (2025). The quest for balance: the journey of energy, environment and sustainable development. *Energy and Environ. Sustain.* 1, 100001. doi:10.1016/j.eesus.2024.12.001

Environmental Kuznets Curve Hypothesis. (2025). *Gondwana res.* 118, 105–116.

Footprintnetwork (2025). GFN global footprint network. Available online at: http://data.footprintnetwork.org.

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

Hashem Pesaran, M., and Yamagata, T. (2008). Testing slope homogeneity in large panels. *J. Econ.* 142, 50–93. doi:10.1016/j.jeconom.2007.05.010

Hussain, Z., Mehmood, B., Khan, M. K., and Tsimisaraka, R. S. M. (2022). Green growth, green technology, and environmental health: evidence from High-GDP countries. *Front. Public Health* 9, 816697. doi:10.3389/fpubh.2021.816697

Irfan, M., Razzaq, A., Sharif, A., and Yang, X. (2022). Influence mechanism between green finance and green innovation: exploring regional policy intervention effects in China. *Technol. Forecast. Soc. Change* 182, 121882. doi:10.1016/j.techfore.2022.121882

Khan, Z., Hossain, M. R., Badeeb, R. A., and Zhang, C. (2023). Aggregate and disaggregate impact of natural resources on economic performance: role of green growth and human capital. *Resour. Pol.* 80, 103103. doi:10.1016/j.resourpol.2022.103103

Koenker, R. (2004). Quantile regression for longitudinal data. *J. Multivar. Anal.* 91, 74–89. doi:10.1016/j.jmva.2004.05.006

Kuznet (2025). *Kuznet, reshape the environmental curve for ecological footprint? Evidence from*.

Li, T., Umar, M., Mirza, N., and Yue, X.-G. (2023). Green financing and resources utilization: a story of N-11 economies in the climate change era. *Econ. Analysis Policy* 78, 1174–1184. doi:10.1016/j.eap.2023.05.007

Mohsin, M., Naseem, S., Zia-ur-Rehman, M., Baig, S. A., and Salamat, S. (2023). The crypto-trade volume, GDP, energy use, and environmental degradation sustainability:

an analysis of the top 20 crypto-trader countries. *Int. J. Finance and Econ.* 28, 651–667. doi:10.1002/ijfe.2442

OECD. (2021). *OECD patents - environmental-related technologies*.

OECD Green Growth Indicators (2020). *OECD statistics. Index. Aspx?*

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *J. Appl. Econ.* 22, 265–312. doi:10.1002/jae.951

Pesaran, M. H. (2021). General diagnostic tests for cross-sectional dependence in panels. *Empir. Econ.* 60, 13–50. doi:10.1007/s00181-020-01875-7

Rafique, M. Z., Fareed, Z., Ferraz, D., Ikram, M., and Huang, S. (2022). Exploring the heterogenous impacts of environmental taxes on environmental footprints: an empirical assessment from developed economies. *Energy* 238, 121753. doi:10.1016/j.energy.2021.121753

Razzaq, A., Sharif, A., Najmi, A., Tseng, M.-L., and Lim, M. K. (2021). Dynamic and causality interrelationships from municipal solid waste recycling to economic growth, carbon emissions and energy efficiency using a novel bootstrapping autoregressive distributed lag. *Resour. Conservation Recycl.* 166, 105372. doi:10.1016/j.resconrec.2020.105372

Ren, Z., and Zhu, Y. (2025). The trade-off between middle class and ecological footprint: empirical cross-country analysis. *Ecol. Econ.* 235, 108631. doi:10.1016/j.ecolecon.2025.108631

Salahuddin, M., Alam, K., Ozturk, I., and Sohag, K. (2018). The effects of electricity consumption, economic growth, financial development and foreign direct investment on CO2 emissions in Kuwait. *Renew. Sustain. Energy Rev.* 81, 2002–2010. doi:10.1016/j.rser.2017.06.009

Sci (2025). *Government competition, and regional green development: Germany: evidence from China*. Sci.

Shang, M., and Luo, J. (2021). The tapio decoupling principle and key strategies for changing factors of Chinese urban carbon footprint based on cloud computing. *Int. J. Environ. Res. Public Health* 18, 2101. doi:10.3390/ijerph18042101

Wang, J., Wang, B., Dong, K., and Dong, X. (2022). How does the digital economy improve high-quality energy development? The case of China. *Technol. Forecast. Soc. Change* 184, 121960. doi:10.1016/j.techfore.2022.121960

Wei, D., Ahmad, F., Abid, N., and Khan, I. (2023). *The impact of digital inclusive finance on the growth of the renewable energy industry: theoretical and logical Chinese*.

Westerlund, J. (2008). *Panel cointegration tests of the fisher effect*. United States: *J. Appl. Econ*.

Wu, Y. Y., Xi, X. C., Tang, X., Luo, D. M., Gu, B. J., Lam, S. K., et al. (2025).

Xu, A., Dai, Y., Hu, Z., and Qiu, K. (2025). Can green finance policy promote inclusive green Growth? based on the quasi-natural experiment of china's green finance reform and innovation pilot zone. *Int. Rev. Econ. and Finance* 100, 104090. doi:10.1016/j.iref.2025.104090

Zhang, C., Khan, I., Dagar, V., Saeed, A., and Zafar, M. W. (2022). Environmental impact of information and communication technology: unveiling the role of education in developing countries. *Technol. Forecast. Soc. Change* 178, 121570. doi:10.1016/j.techfore.2022.121570

Zhang, Y., Ding, Y., and Yan, W. (2025). United in green: institutional dual ownership and corporate green innovation. *Finance Res. Lett.* 84, 107814. doi:10.1016/j.frl.2025.107814