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Green growth and sustainable energy transitions: evaluating the critical role of technology, resource efficiency, and innovation in Europe's low-carbon future

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Renewable energy, technology, and innovation are central to sustainable development, but their effects vary by country because of institutional and economic differences. Previous studies often ignore these differences. By incorporating institutional and economic differences, our study aligns with a growing body of research emphasizing the importance of context in evaluating sustainable development strategies. This nuanced approach allows us to contribute to the ongoing debate by offering a more comprehensive framework for understanding how renewable energy, technology, and innovation interact with the broader economic and institutional environment to drive sustainable outcomes. This study provides a comprehensive analysis to investigate the determinants of green growth in European economies with changing income (higher, upper middle, and lower income) levels. For this study, we have taken data from 1990 to 2023 and employed the Cross Sectional Autoregressive Distributed Lag model. The empirics show that renewable energy consumption and economic growth significantly enhance the green growth across all income groups. One percent increase in renewable energy consumption leads to increase the green growth by 0.1488, 0.0965, and 0.1613 percent respectively while one percent increase in GDP leads to increase green growth by 0.24, 0.26, and 0.32 percent for higher, upper-middle and lower middle-income countries respectively in long run. Nevertheless, technological innovation and globalization show mixed results, being more effective in higher income economies due to stronger institutions and green innovations. More precisely, one percent increase in technological innovation leads to rise green growth by 0.0762 percent in higher income economies while it shows insignificant result for upper and lower middle-income economies. On the other hand, one percent increase in globalization leads to decrease green growth by −0.1439 percent in upper middle income only while it shows insignificant result for high and lower middle-income economies. Furthermore, Natural resource rents generally enhance green growth particularly in lower income economies, supporting resource curse hypothesis. One percent increase in natural resource rents leads to rise green growth by 0.0159 percent in lower middle income. The findings emphasis the need for income specific state policy that promote sustainable development. The policymakers should focus on clean energy investment, green innovation and strengthen institutional frameworks to ensure sustainable green growth.

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Introduction

Background of the study. Sustainable development (SD) enables the nations to survive in the long term. Sustainability empowers the economies to meet their objectives that involve protecting the environment, safeguarding the society and growing the economy. Over approaches that are equally stable to the environment, sustainability benefits the economy all at once and cares about the well-being of society. The world is currently dealing with several issues, but the most significant ones that are also mentioned in the Sustainable Development Objectives are poverty, inequality, injustice, and global climate change (Bai et al., 2022). According to the UN 2030 Agenda of Sustainability, the three main pillars of Sustainable Development are economy, environment & society. Every pillar of SD supports the others (Sharpley, 2020; Chien, 2022). Often, achieving high growth and sustainability are seen as two different goals, especially when technological advancement is thought to have negative ecological repercussions (Hübler et al., 2012). Information and communication technology stimulates productivity and energy efficiency in the digital phase.

The environmental problem of employing technology sets is thought to be solved by innovative technology utilization, especially in the energy industry (Al-Mulali et al., (2015)). Technological developments assist in pointing out environmental issues like greenhouse gas emissions and spur eco-innovation in the nation. The nation is moving towards sustainable development because of the environment as well as the resources saved from greenhouse gas emissions (Sadiq et al., (2023); Sadiq et al., (2023) and Yuan and Zhang 2020). In the fresh years, Information and communication technology in BRICS nations is also growing fast, that has a great influence on its development. According to Franceschini and Pansera (2015), the debate of sustainable development restored the certainty that technological advancements are essential to maintaining both environmental sustainability & Economic Growth (EG). In the outcome, awareness has been raised regarding environmental issues (cleaner technologies are one example) which Paredis (2011) views as means of addressing both environmental & development issues simultaneously. Technological innovation has an instrumental function in the economic, social and environmental spheres which makes it a crucial component of sustainable development (Fokkema et al., 2005; Constantinescu and Frone 2014). To promote the GG (Green Growth), technology innovation is key in lowering the costs of environmental protection.

Besides technological innovation, renewable energy consumption also plays a driving role for sustainability of nations. One significant instrument for encouraging the growth of renewable energy (RE) is the Sustainable Development Goals (Wang et al., 2022). In fact, the SDGs' seventh goal is to assure that everyone is accessible to low-priced, safe and sustainable energy (He et al., 2022). This indicates that nations, businesses and people are devoted to progressing the growth of sources of renewable energy (RE) including wind, hydropower, and solar (Schwerhoff, Sy (2017). Renewable energy is considered as sustainable & clean energy source that may be used to fulfil energy requirements in countries. Several advantages are provided by renewable energy that can assist nations, corporations, and individuals in achieving the SDGs (Cheng et al., 2021). Choudhury et al., (2023) explore the environmental impact on top polluted economies of the world and found that energy consumption and GDP has positive and statistically significant influence on CO_2 emissions. Akbar et al. (2024) investigated the impact of renewable and non-renewable energy sources on carbon emissions in SAARC countries. The study findings show that non-renewable energy consumption enhances CO_2 emissions while renewable energy consumption decease CO_2 emissions. Nosheen et al., (2024) also found that renewable energy is the main source of sustainable development.

Examining the connection between renewable energy (RE) and the SDGs is crucial because this can be helpful for nations in achieving sustainable development and uplifting the living standard for their residents (Boubaker, Omri (2022)). SDGs upholding can be improved by renewable energy in a number of ways. According to (Marco-Lajara et al., (2023)), renewable energy can support in lowering greenhouse gas emissions which will support SDG 13 efforts to alleviate the consequences of climate change. Furthermore, SDG 7th, which demands worldwide access to modern, reasonable, safe, secure & sustainable energy (SE) services, can be aided by renewable energy making energy more reachable to people everywhere. Moreover, by generating both direct & indirect jobs in industries like infrastructure development etc., the transition to renewable energy sources can increase employment. This can help achieve SDG 8, which demands productive & full employment, decent work for all, and sustainable economic growth as explored by (Bertheau, 2020).

Natural resource rent is also important indicators of sustainable development. Ji et al. (2023) explored that efficient use of natural resources is required to promote sustainable and sound financial development. Moreover, natural gas rents and mineral rents positively affect global economic growth and hence lead to boost global sustainability (Fu and Liu, 2023). According to Azam et al. (2023), total natural and oil rents positively contribute to sustainable development, while coal rents have negative and forest rent has an insignificant impact over it. Economic indicator like GDP is also crucial when discussing sustainable development. Sustainable development means steady economic growth that does not reduce natural resources or endanger the ability of future generations to meet their own needs (Erdogan, 2024). The connection between GDP and sustainable development relates to wealth distribution and equity (Shao et al., 2023). Often, inadequate economic growth results in socioeconomic inequalities which can be incompatible with sustainable development. Alsagr and Ozturk (2024), Azam et al. (2023) indicate that economic growth contributes significantly and positively to sustainable development. However, others came up with a conclusion that the effect is negative by worsening environmental quality (Anwar et al., 2022).

The current study is distinguished from existing literature in number of ways. Available research has explored the variables separately or investigate the case of individual countries, however, this study applies the European countries aggregation with panel data methods. Moreover, on the natural resource management side, GHG emissions have been focused by earlier studies which is not the case here in this study. This study takes green growth as a proxy for sustainable development to explore something new. Additionally, the current study along with technological innovation and renewable energy consumption as focused variables, used some controlled variables like GDP, GDP square as a proxy for Environmental Kuznets Curve (EKC), Natural resource rents and Globalization index which is further decomposed into economic and political globalization. The results of all these variables will show how these can drive sustainable development (Green Growth) in European countries.

This study is carried out to answer the essential research question that how do technological innovation and renewable energy consumption contribute to green growth, which is taken as a proxy for sustainable development across diverse European economies? This study aims to explore the composite effect of technological innovation and use of renewable energy on the sustainable development in case of European economies as a proxy variable by using green growth.

Motivation of the study. The motivation for the study stems from increasing policy concern for sustainable development within the framework of environmental challenges and economic transformation in emerging economies. By establishing key drivers of green growth, the results provide policy implications that can inform European countries to develop holistic strategies for sustainable development.

Contribution of the study. This study makes three significant contributions to the existing literature. First, it extends the analysis of green growth beyond high-income economies by including upper- and lower-middle-income European countries, allowing for an income-based comparative outlook that is largely omitted by previous studies. Second, it provides empirical evidence on the combined effect of technological innovation, renewable energy consumption, natural resource use and globalization over sustainable development that is measured through green growth. Third, it bridges the gap between environmental economics and innovation policy by examining how these forces interact in shaping low-carbon transitions by offering different intuitions for both policy design and academic debate in the European context.

The remainder of this study is organized as Section “Literature review” covers the relevant literature review including literature gap and theoretical framework in subsections. Section “Data and Methods” covers the data and methods including discussion on variables and econometric methodology. The next section contains estimation results based on econometric tests and techniques with discussion over it. Finally, the last section is conclusion of the study and policy recommendations based on findings.

Literature review

Studies on green growth and its impact have received significant attention in recent years. Keeping our research objectives under consideration, we have accumulated the summary of research across our major themes. Here we have provided some studies that will help us to identify the potential research gaps.

Nexus between green growth, sustainable development & natural resources. Xu et al. (2022) studied the green growth, sustainable development & natural resources for BRICS economies for the time 1991–2014. By using panel data methods like slope heterogeneity, cross sectional dependence & the MM quantile regression model, the authors explored that green growth shows a heterogeneously influence the economic performance in BRICS. Furthermore, green innovation is negatively linked, although renewable energy consumption & natural resources were found to be the leading features of economic performance. Omri (2020) discussed technological innovation and SD in 75 low, middle & high-income nations. By putting the DOLS and VECM models, the author found that technological invention is the reason for environmental, economic, and for the social scopes of sustainability in nations only with high income, while it only results in the economic & environmental scopes in economies with middle income. No causal associations were noted in economies with low income. Fokkema et al. (2005) with an intensive view on social & environmental scopes of economic growth found that technology is a major aspect for sustainable development. Some researchers think that, considering a significant improvement in efficiency of environment and manufacturing of goods & services, technological advancement should be deeply focused for guaranteed sustainable development.

Liu et al. (2024) conducted an asymmetric study of environmental quality towards sustainable development in case of UAE. The natural resources, renewable energy and export diversification are taken as variable of interest using the time period of 1990 to 2019. To explore the empirical findings, the nonlinear autoregressive distributed lag or NARDL and dynamic ordinary least squares or DOLS techniques have been used. Empirical evidence substantiates that export diversification, natural resources and economic growth adversely affect the UAE environment by accelerating carbon emissions. In this respect, positive and negative shocks of export diversification, natural resources, and economic growth increase and decrease carbon emissions, respectively, while positive and negative shocks of renewable energy decrease and increase carbon emissions. Udemba and Yalçıntaş (2021) examined that how FDI, natural resources as well as economic growth determine the environmental performance of Algeria, in other words, to study the sustainable development of the said country. To do so, the authors used the nonlinear autoregressive distributed lag NARDL model using the time frame of 1970 to 2018. The findings disclosed that economic growth and Algerian fossil fuel shocks have opposite consequences on carbon emissions (increasing and decreasing, respectively). However, FDI and natural resource shocks consistently result in decreased carbon emissions which are beneficial for the Algerian environment.

Ahmad et al., (2023) also explored that technological modernization is a crucial factor that encourages SD in China. The author by using the ARDL approach revealed that innovation is helpful for causing SD by decreasing pollution created by environment and improving the China’s growth. The author further discovered that financial expansion also donates significantly to sustainable development of China with the help of decline CO2 emissions. Bekhet & Latif (2018) studied the impact of technological innovation and institutional quality for attaining sustainable growth for the period 1995–2015. The authors exposed that alliance of governance & technological innovation adds positively to sustainable growth of Malaysia. Constantinescu & Frone (2014) argued that technological innovation (TI) has a vital role in advancing SD over its influence on three pillars of sustainability & also with conclusive impact on the attempts to encourage economic strength, social progress and sustainability of environment.

Wang et al. (2022) illustrated the influence of technological modernization on green TFP that led towards sustainable development. Taking the OECD economies for the period 1996–2017, the author used the threshold regression model. It was revealed that technological advancement has significantly and positively influenced the green total factor of productivity that promotes sustainable development. Moreover, Suki et al. (2022) suggested that the company putting on technology innovation supports sustainable growth. The author analyzed technological advancement with its effect on environmental and sustainable development. It was concluded that advanced technology along with usage of reprocessing energy helps performing business developments with no greenhouse gas emissions. So, technology innovation cares for sustainable growth. According to Silvestre, Ţîrcă (2019) studied the role of technological innovation (TI) in diminishing greenhouse gas emissions & attaining sustainable expansion. The authors found that minimizing GHG emissions and a healthy environment offer strong human resources to sustainable development. Thus, technological advancement has an inverse relation with GHG emissions. Güney (2019) investigated how renewable energy and nonrenewable energy affect sustainable development. By using the panel data for 40 developed and 73 developing nations, the author employed the System-GMM and IV (2SLS) techniques and found that renewable energy has a positively and significantly influence the sustainable development both in advanced & developing economies. As there is a rise in renewable energy, the level of SD also goes up as explored by the author. It was also stated that comparatively, the impression of RE is more than that of non-renewable (NR) energy. Moreover, Zhang et al. (2021) investigated the association of ecotechnology innovation, economic effectiveness & the performance of economic wellbeing with sustainable development. By applying the 2 stage super slack based measure (SBM) taking 102 economies, it was found that there exists a positive linkage between advancement in technology and SD. Lyeonov et al. (2019) has studied the impact of green investment and renewable energy on greenhouse gas emissions and sustainable development (SD) in case of European Union from 2008–2016. Using the modes of FMOLS & DOLS, the outcomes showed that renewable energy use reduces the GHG emissions & hence increases environmental well-being which supports sustainable development. Moreover, Yu et al., (2023) analyzed how green growth in China is influenced by natural resource rent, economic stability and the legal framework. Using the ARDL model for the period 1980–2021, the authors found that economic risk is a hurdle towards green growth while natural resource rent and governance indicators drives the green growth in China.

Accordingly, Vasylieva et al. (2019) proposed a study on renewable energy's effects on GHG emissions and sustainable development using the hypothesis of Environmental Kuznets Curve in Ukraine & EU nations. The researchers used the FMOLS and DMOLS methods for the period from 2000 to 2016. It was revealed that renewable energy reduces GHGs, and environmental protection raises sustainable development. Udemba et al. (2024) worked out a study on the significance of financial development, technological innovation, renewable energy, and export diversification to attain long-term environmental quality in case of China. Applying the ARDL model and Granger causality test for the period of 1995Q1 to 2018Q4, it was revealed by the authors that technological innovation and renewable energy have valuable influence on the environmental quality while economic growth and export diversification have damaging impact on the environmental quality of China. Moslehpour et al. (2023) focused on the dynamic connectivity among Technological development, green finance, Energy efficiency and Sustainable development in Vietnam using the period 1991–2020. The authors with the Dynamic Autoregressive Distributed Lags & the Bayesian Autoregressive Distributed Lags model, explored that green finance, advanced technology, renewable energy (RE) output, renewable energy (RE) consumption, population rise & industrialization found to have a positive link with sustainable development in Vietnam.

Similarly, Sueyoshi et al., (2022) by using the nonparametric method called as Data Envelopment Analysis (DEA) explored that the segment of RE in total consumption of energy has positively and strongly influenced sustainability. The author studied how renewable energy affects sustainability at country level for the period 1990–2014 and found that renewable energy strongly and positively improves sustainability of the world. According to Cerqueira et al., (2021), renewable energy and recycling processes of waste are contributing meaningfully to improve the OECD countries' level of sustainable development. The study was an attempt to analyze the connections among renewable energy, recycling & economic development using the data for the period 2000–2016. It was revealed that both recycling & renewable energy are significant policy aspects for creating sustainable development in OECD countries. Liu et al. (2023) investigated that whether renewable energy is a provides a path towards sustainable development in United states during the period 2013–2022. The test of Granger Causality was practiced examining the linkage between RE and sustainable development. Moreover, the bivariate VAR model revealed that RE influences sustainable development both in positive and negative manners. Similarly, Udemba and Alola (2022) used nonlinear ARDL approach and explored that the positive shocks to renewable energy result in reduction of carbon emission by 23 percent while in case of negative shocks, the carbon emission is raised by 16 percent. This highlights the significant role of renewable energy in attaining environmental sustainability which is a core pillar of sustainable development.

Moreover, Işık et al., (2024) employed the CS-ARDL model and discovered that economic and environmental factors are positively linked with natural resource rents indicating that sustainable environmental practices are important in expanding resource profitability. Moreover, the authors found that governance factors and technological innovation negatively influence the natural resource rents while SDGs also have a positive association with natural resource rents. In their second paper, Işık et al. (2024) investigated the impact of environmental, economic, social, and governance factors on SDG based energy efficiency in case of G-7 countries. Using the CS-ARDL model, the authors came with findings that economic factors relate negatively, while environmental factors relate positively with SDG based energy efficiency. To emphasize the importance of green policies in attaining SDG goals, Iqbal et al. (2024) used more advanced techniques that are panel-correlated standard errors (PCSE) and the Driscoll–Kraay estimations (DKSE) models and explored that green human capital, consumption of renewable energy, and quality institutions are found to considerably minimize CO2 emissions. However, artificial intelligence, geopolitical risk, natural resource rent, and information communication technology lead to rise CO2 emissions.

Gaps in the existing literature. Although there has been a significant amount of literature that has analyzed the intersection of technological innovation, renewable energy, and sustainable development but has focused mostly on countries like BRICS and USA. Moreover, most of the literature has only analyzed these variables separately, and minimal effort has been directed to the analysis of the individual and joint impacts of technological innovation and consumption of renewable energy on green growth which is a comprehensive stand-in for sustainable development on the wider European continent, encompassing categorization of income levels as well. Additionally, most studies ignore the heterogeneity of technology adoption and policy response in Europe, especially for countries facing diverse economic and environmental issues. This paper closes this research gap by exploring how the advent of renewable energy deployment affects European green growth and how technological change plays a role based on an innovative econometric strategy that accommodates cross-sectional dependence and heterogeneous dynamics in European countries.

The European countries are some of the world's major and fast-growing economies. Due to their considerable populations, manufacturing centers and resource consumption, they have major influences upon environmental issues everywhere. Because of this impact, knowing sustainable practices and means to drive sustainable growth and development around the world is significant in European nations. That is why the current study with a particular focus on European nations, will show that technological advancement and natural resource management, specifically renewable energy could be the driving forces of sustainable development.

Theoretical framework. The foundation of the theoretical instrument, through which natural resources (NR), with technological innovations (patent), Renewable energy consumption, Natural resource rent, Gross domestic product, and globalization affect green growth, is explained in this section. Natural resource rent, technological innovations, Gross Domestic Product (GDP), and globalization are all interconnected and have a significant impact on the concept of green growth. The following paragraphs explain the theoretical mechanism through which these factors affect green growth.

Technological innovation contributes to the change of economies' industrial and financial structures, while facilitating the encouragement of green growth. It is feasible to employ "patents" as a proxy for technological innovations, to identify significant points of origin for innovative technology intended to tackle environmental issues. A rising corpus of mostly policy-oriented research supports the intuition that patenting serves as a helpful, if not perfect, indication of the locations of new idea creation in the "green economy" (Tanner et al., 2019). Hence, following Popp (2010) and Khan et al., (2020) forecast that technology innovation will almost certainly have a favorable impact on GG (green growth) as $\lambda 1 = \partial GG/\partial TI > 0$. In the same manner, Manderson & Kneller (2012) and Saleem et al. (2022), also anticipated that technological innovation will have a favorable impact on green growth. SDG 17 aims to achieve all goals through extensive collaboration in all pertinent areas and the use of proactive alliances. The ultimate objective is to contribute to free access to scientific and technological information for sustainable development and growth. Technological innovations also contribute significantly to fostering green growth. Industries may implement eco-friendly technologies to help the environment by making investments in the green technology sector. The literature on how economic activity and globalization affect the rise of green growth offers contradictory findings. Globalization is an international phenomenon that has an impact on people's lives on a social and political level everywhere in the world (Bekun et al., 2020). In terms of negative impacts, however, globalization has a greater positive impact, especially when it comes to the elimination of poverty in rising nations and income disparity. While some studies (Ulucak & Khan, 2020; Christmann & Taylor, 2001; & Xu et al., (2018)) demonstrated that globalization can raise CO2 emissions, other researchers (Acheampong and Boateng, 2019; Akadiri et al., (2020)) demonstrate the contrary. Particularly, because of new business opportunities, the complicated shape of the relationship between transactions, GDP, & GG could vary as income, technology use, and macroeconomic structure change. To make this study more concrete this study also divided globalization into economic and political globalization (PG). In supplement to influencing economic advancement, economic globalization (EG) which is characterized by the cross-border trade of products & services, global capital mobility and technological transfer also channels its effects on green growth sustainability (Ahmad, Wu (2022)) and Political globalization, through international agreements and cooperation, can provide a framework for addressing global environmental challenges. If the technique's impact outweighs the size effect, globalization plus GDP may have a favorable effect on green growth as $\lambda 2 = \partial GG/\partial GL > 0$. But be careful, the opposite is also true.

The author explored difficulties with environmental degradation brought on by the natural resources' depletion. Natural resources are the foundation of economic growth (EG) and development. They are essential to produce goods & services, and their availability and quality are critical determinants of economic performance (SDG 17). Using natural resources, though, has negative consequences for the environment, such as pollution, deforestation, and climate change. Green growth goal is to settle economic growth with sustainable environment by promoting the efficient use of natural resources and the development of renewable resources as $\lambda 3 = \partial GG/\partial NRR > 0$. Countries aiming for the highest economic growth in this initial stage have drastically decreased environmental quality. Beyond this early phase, the economies' key objectives are to establish environmentally friendly policies to reduce CO2 emissions while achieving sustained financial stability and growth for the economy. Environmental economists and other decision-makers have used the study of EKC's hypotheses involving incomes, pollutants, & other crucial factors in the Gross Domestic Product square function as $\lambda 4 = \partial GG/\partial GDP > 0$. The EKC phenomena can be used to elaborate the relationship between environmental deterioration & growth. Following up on Kuznets' research, Grossman & Krueger (1991) divided the relation-ship between environmental quality & growth into three stages. The EKC channel is also debated for SAARC by (Yikun et al., 2021 and Li et al., 2021) for Globe (Dinda & Stern, 2004) for Asia (Apergis and Ozturk, 2015) for Kenya (Al-Mulali et al., (2015)) for OECD (Jebli et al., 2016) as $\lambda 5 = \partial GG/\partial GDP^2 > 0$. Renewable Energy consumption is sometimes termed as a machine of economic mechanism. Academia/ Scholars have practiced econometric methods and revealed that energy consumption (EC) is the key source of green environment sustainability and troubled and improved the climatic conditions of many countries (Caglar (2020)) as $\lambda 6 = \partial GG / \partial REC > 0$.

To enhance conceptual clarity, Fig. 1 below shows the visual representation of the theoretical framework. The direction of relationships will be explored empirically and may differ across income groups.

Data and methods

Data and variables description. This study provides a comprehensive analysis to investigate the determents of green growth in European economies with changing income (Higher, Upper middle and lower income) levels. For this study we have taken data from 1990 to 2023 from different sources. Our dependent variable green growth is constructed as GDP per capita divided by CO_2 emissions, while independent variables are Natural resource rents, renewable energy consumption, GDP and technological innovations. All variables' data has been taken from WDI except KOFGI, which is obtained from KOF Swiss Economic Institute. Authenticity of data is guaranteed by drawing all variables from internationally accepted and reputable databases like the World

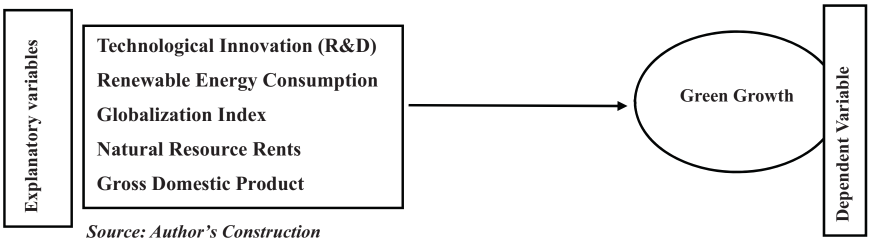

Fig. 1 Conceptual framework of the study. Source: Author's Construction.

Table 1 Summary of data description and sources.

Variables	Symbols	Sources	Units
Green Growth (GDP/CO_2 emissions)	GG	WDI	CO_2 (Metric tons per capita)
Technological Innovation (R&D)	TI	WDI	% of GDP
Renewable Energy Consumption	REC	WDI	% of total final energy consumption
Globalization Index	KOFGI	KOF Swiss Economic Institute	Index (0–100)
Natural Resource Rents	NRR	WDI	% of GDP
Gross Domestic Product	GDP	WDI	Constant US $ 2015

Source: Author's own compilation.

Bank (WDI) and KOF Swiss Economic Institute which are used extensively in empirical economic studies due to their reliability, transparency, and consistency. Table 1 below further clarifies the description and sources of the data used in the current study.

Justification of selected variables
Technological innovation (R&D expenditure): R&D fosters technological advancements that lead to more efficient, cleaner production methods and energy solutions. These innovations can reduce CO_2 emissions while supporting economic growth. Increased R&D investments can drive technological changes that decouple GDP growth from environmental harm, supporting sustainable development (Romer, 1990; Porter, Linde (1995); Horbach et al., 2012).

Renewable energy consumption: Shifting from fossil fuels to renewable energy sources reduces CO_2 emissions, a critical factor in green growth. Higher renewable energy consumption helps decouple economic activity from carbon emissions. Increased renewable energy use lowers the carbon intensity of GDP, fostering sustainable economic growth (Stern, 2004; Apergis & Payne, 2010; Omri & Nguyen, 2014).

Globalization Index: Globalization influences both economic growth and environmental impact through trade, investment, and technology transfer. It can increase economic growth but may also raise environmental pressures unless accompanied by green technology diffusion. Globalization can thus stimulate green growth if paired with strong environmental policies (Grossman & Krueger, 1991; Shahbaz et al., 2018).

Natural resource rents (% of GDP): Resource rents from the extraction of natural resources can either promote or hinder green growth depending on governance and institutional quality. Mismanagement often leads to environmental degradation and higher emissions, while prudent use can finance green infrastructure and technology. This supports sustainable development if resource revenues are invested in diversifying the economy and reducing carbon intensity (Sachs & Warner, 2001; Van der Ploeg, Venables (2011); Bhattacharyya & Hodler, 2010).

Gross domestic product (GDP): GDP represents the level of economic output and is an essential part of the green growth measure. While economic growth typically raises emissions (scale effect), it also enhances capacity for adopting cleaner technologies (technique effect). Green growth occurs when GDP increases without a proportional increase in CO_2 emissions, i.e., when growth is decoupled from environmental degradation (Kuznets, 1955; Stern, 2004; Dinda, 2004).

Model specification. To investigate empirically how technological innovation affects green growth when GDP, REC, natural resource rent, and globalization is present. The empirical equation may be modeled as:

$$GG_t = \lambda 1 TI_t + \lambda 2 GL_t + \lambda 3 NRR_t + \lambda 4 GDP_t + +\lambda 5 REC_t + \mu_t \tag{1}$$

Where GG stands for green growth, which is the dependent variable, representing the level of sustainable economic growth & development achieved whereas minimizing negative environmental effects. GL stands for economic and political globalization and TI represents for technological innovation and its proxy Research and Development expenditure, REC for renewable energy consumption, NRR represents natural resource rent, and GDP shows gross domestic product. The empirical equation may be estimated using regression analysis, with data collected from European countries over a specified period. The results of the analysis will help to determine the extent to which technological innovation contributes to green growth, and whether this contribution is significant even when controlling other factors such as GDP, natural resource endowment, and economic globalization.

Econometric methodology.

$$\Delta GGit = Ci\ Þ\lambda i\ (\bar{GG}_{it-1} - bi\bar{X}_{it-1} - YiC_{it-1} - f1iG\underline{G}_{t-1} - d2X_{t-1} - p2C_{t-1})$$
$$+\textstyle\sum_{j=1}^{p-1} \theta ij \Delta\ GGit - j + \sum_{j=0}^{q-1} \eta ij \Delta\ Xit - j + \sum_{j=0}^{q-1} \phi ij \Delta\ Cit - j \tag{2}$$
$$+ h1i\Delta\ GGt + h2i\Delta Xt + h3i\Delta Ct + \varepsilon_{it}$$

In above Eq. 1, green growth (GG) is our response variable while renewable energy consumption (REC) and Technology Innovation (TI) are the focus explanatory variables. The other independent variables, such as natural resource rent (NRR), gross domestic product (GDP), globalization index (GI) and economic globalization (ECGI) are control variables. We are mainly interested in controlling the pertinent cofactors for a subset of economies involved in the One Belt One Road Initiative to analyze the impact of technological innovation and the use of renewable energy on green growth. The selection of these variables is rooted in economic theory and supported by recent empirical evidence (Moslehpour et al., 2023; Liu et al., 2024). Technological innovation and renewable energy are listed as key drivers of green growth, and GDP as an indicator of economic performance. Natural resource rents and globalization are included to reflect environmental pressures and external influences, respectively.

For empirical analysis, this study will use an augmented version of the traditional panel ARDL-PMG (Pesaran et al., 1999) which is known as Cross-Sectionally Augmented Autoregressive Distributive Lag (CS-ARDL) model by Chudik and Pesaran (2015). The model's authenticity and applicability are guaranteed as it is the most appropriate model for panel data settings such as European nations that may be characterized by cross-sectional dependence, heterogeneous dynamics, and non-stationarity. The model allows for both short-run and long-run estimation and also helps in attaining a global optimum solution by including cross-sectional averages which adjusts for omitted variable bias and potential endogeneity. This makes it effective for investigating the changing impact of technological innovation and renewable energy on sustainable development (green growth) across different income groups. As discussed above, the current study extracts those factors which are causing damaging effects on green growth. Before applying the suitable estimation techniques to the selected data series, we need to verify if the variables under study are stationary. For this, we exercise the co-integration test to check the order of integration by considering unit root test. In this context, the time under examination considers the changes and transformations that occur, as these primarily lead to structural breaks. The other typical unit root test for example ADF; DF-GLS and KPSS generally don't give structural breaks, resulting in inconsistent & biased outcomes (Umar et al., (2020)). The benefit of this technique is that, unlike the more traditional unit root test approaches that are frequently considered, the structural breaks that occur in this part do not exert any influence while the data is being processed. Following stationary testing, Bayer and Hanck's (2013) teachings are used for looking into the co-integrative link between the variables that were currently considered. It is notable to observe that this upgraded co-integration approach tends to produce results that are far more precise in nature. This is achievable because the results of numerous tests are merged to provide a single result. Engle and Granger (1987), Johansen (1991); Boswijk (1994) & Banerjee et al. (1998) are few of the tests that fall under this category. As a result, the equations of Bayer-Hanck Fisher are shown below:

$$EG - JOH = -2[ln(PEG) + ln(PJOH)],$$

$$EG - JOH - BO - BDM = -2[ln(PEG) + ln(PJOH) + \ln(PBO) + \ln(PBDM) \quad (3)$$

In the above Eq. 2, the symbols PEG; PJOH; PBO & PBDM stand for the probability values corresponding to each of the co-integration tests that were described earlier.

Furthermore, the Fisher statistics setup establishes the nature of the long-term relationship between the central variables. Following the study uses the Maki co-integration test, which was created by (Maki, 2012) and considers a variety of structural breaks. Maki co-integration test, in contrast to other co-integration tests that involves structural breaks (Hatemi-j, 2008), has a very well-defined magnitude and qualities of influence, according to writers like (Cheng et al., 2021). This is because ignoring the presence of additional structural breaks can lead to biased and inaccurate estimates of the model parameters and their associated statistical significance. Multiple structural breaks can have significant impacts on the underlying relationships between variables. Therefore, it is important to conduct a thorough analysis that considers the possibility of multiple structural breaks and accounts for their potential effects on the data.

The present test additionally considers the DOLS & CCR, which were proposed by (Saikkonen (1992)), (Watson (1993)), and (Park, 1992), as well as the Fully Modified OLS that was popularized by (Phillips and Hansen, 1990). The test is considered in order to find any potential long-term impacts of Technological-innovation, Globalization, GDP, Natural resource, and GDP square on GG in BRICS. To get around this correlation problem, Phillips & Hansen (1990) also devised the Semi-Parametric method called FMOLS. The FMOLS test tends to be asymptotically unbiased and proactive in nature, they highlighted. The FMOLS and CCR have been replaced by another approach that was originate by (Park, 1992).

The primary distinction among the Fully Modified OLS and the CCR estimators in this context stems from the fact that, whereas the FMOLS concentrates on the reconstruction of data as well as the appropriate parameters, the CCR estimator frequently concentrates solely on changing the data (Hassan, Abubakar (2025)). In addition, the DOLS estimate makes use of lags and leads to the loss against simultaneity biases and small number of samples error. In particular, when analyzing, DOLS & FMOLS estimation methods must contend with the challenge of resolving the endogeneity as well as serial correlation issues by controlling the disturbance factors (Su et al., (2020)). The current study also makes use of the Causality test, which was first created by (Geweke (1982)) & (Hosoya (1991)) & later refined by (Breitung & Candelon, 2006) for the purpose to take into consideration the causal link.

Results and discussion

Table 2 gives the summary statistics of all the variables. The total number of observations has 1496, which is reliable sample size for statistical analysis. The most of the variables Mean and Median are fairly close except lnIT which is negatively skewed. The high mean was observed for a variable lnGG (21.5), indicating that these countries are relatively high growth. The value 2.37 of lnNRR variable for standard deviation shows mostly dispersed while the standard deviation of the lnKOFGI is 0.23 showing low variation in globalization across sample. Here, the skewness values indicate that most of the variables are negatively skewed which means that variables have longer tail to the left side. A very high kurtosis value reported for the varible lnIT (21.83), while other variables lnNRR, lnREC, and lnKOFGI are moderately leptokurtic, meaning that some outleirs and sharp peeks in distribution.

Table 3 demonstrates the findings of the Cross-Sectional Dependence (CSD) for all variables used in the model. This test was proposed by Pesaran (2004) with an argument that cross sectional dependence exists in panel data. We reported that the CD test statistics are highly significant for all variables, indicating that there is a strong cross-sectional dependency across countries or panel. The average and absolute correlation values for variable lnKOFGI (0.95), lnGG (0.86) and lnGDP (0.84) showing a very

Table 2 Descriptive Statistics.

Variable	LnGG	lnTI	lnGDP	lnNRR	lnREC	lnKOFGI
Obs	1,496	1,496	1,496	1,496	1,496	1,496
Mean	21.518	−0.181	9.567	−1.12	2.317	4.243
Median	21.6537	0.03998	9.73546	-0.9062	2.5177	4.32301
Std. Dev.	0.933	1.338	1.129	2.378	1.197	0.23
Variance	0.87047	1.79155	1.27498	5.65555	1.43383	0.05272
Min	18.78	−12.045	6.558	−12.114	−2.303	3.216
Max	23.87	6.609	11.63	5.872	4.418	4.498
Skewness	−0.345	−2.632	-0.406	−0.784	−0.941	−1.654
Kurtosis	2.73	21.831	2.299	4.685	4.324	5.895

high positive correlation among different cross sections. Even variable lnNRR and lnTI showing lower correlation coeffects but still exhibits significant dependance. After recognizing the cross-sectional dependence, next is to explore the stationarity property of the variables.

We have employed the first generation (LLC and IPS) proposed by Levin et al. (2002) and Im, Pesaran and Shin (2003) respectively. Moreover, the second generation (CADF and CIPS) panel unit root tests proposed by Hansen (1995) and Pesaran (2007) respectively, is also applied to determine stationarity of the variables. In Table 4, across all four panel unit root tests showing that most of the variables are non-stationary at level I(0) but become stationary after first differencing I(I). If we look it the table variable lnGG at level it is not stationary at all tests so we fail to reject the null hypothesis of a unit root test. At first difference, all tests strongly reject the null hypothesis because green growth variable is stationary at first difference. A variable LnIT also non-stationary at level in all panel while stationary at first difference. Gross Domestic Product variable is stationary at level I(0) in panel LLC, CADF and CIPS while at first difference stationary at all panels. A lnREC stationary at mixed order reported in the table. Natural resource rent variable is non stationary at level while stationary at first difference. In sum, both the first- and second-generation panel unit root tests resulted the mixed order of variables for stationarity which means that we will have to perform the ARDL model approach for estimation. Before going towards process of estimation, it is quite relevant to explore the existence of long run relationship among the variables. For this objective, we have applied for the Westerlund (2005) and Pedroni (1999, 2004) cointegration tests. In Table 5 we have applied both test for checking either long run relationship exist among the variables in the panels. We observed that the values of Pedroni cointegration test are statistically significant, suggesting that there is long run relationship exists among the variables. While Westerlund test values are insignificant showing no long run relationship exists. But literature suggest if you still want to explore long run relationship you can apply on the basis of Pedroni test which suggest the long run relationship exists among variables.

The estimated outcomes from the Cross Sectional Autoregressive Distributed lag (CS-ARDL) model are shown in Table 6. The variable technological innovation (lnTI) indicates a positive and significant impact on green growth in both the short and long run in the European Economies. Its coefficient in the short run is 0.067 while in the long run is 0.03 and statistically significant. Our finding is consistent with Bekhet & Latif (2018), Sun et al. (2023) and Kwilinski et al. (2025), who also discovered the positive impact of technology innovation on sustainable development. GDP is also a significant positive impact in both the periods, indicating that economic growth is a major indicator of green growth in this region. It long run coefficient value is 0.32 showing that if one percent increase in GDP leads to green growth by 32 percent in the European region. Renewable energy consumption (lnREC) has also reported positive and significant impact on green growth. It showing that clean energy adaptation is important for achieving environmental goals. This finding supported by Güney (2019), Moslehpour et al. (2023) and Khan et al. (2025). The remaining variables lnNRR and lnKOFGI both are insignificant, demonstrating that in the context of Europe may be resource dependency and globalization don't play a direct role in driving green growth in the long run, may be due to strict environmental laws and diversified economies in Europe. It is a usual recognition that economies are heterogeneous in their gross national income and can have different behavior of various economic variables. The results presented in Table 6 can be misleading if these were driven by only a certain group of economies. To avoid this uncertainty about the findings we have decomposed our data set into three groups based on income. The subsample classification contains the higher income nations, upper middle-income countries & lower middle-income countries. This study estimates the same model (CS-ARDL) separately for three sub samples.

The empirically estimated results of the CS-ARDL presented in Table 7 based on different income groups (Higher income, Upper middle income and Lower middle income) countries. It will explain that how different macroeconomic variables influence green growth in European economies. If we look at the long run estimates, lnTI coefficient value is 0.076 which is positive and significant in higher income economies, indicating that R&D and clean innovation promoting green growth in these regions while insignificant impact reported in upper and lower middle-income countries due to weak innovation ecosystems in these economies. Economic growth variable (lnGDP) shows a positive and significant relationship with green growth in all three income groups. This can be explained that if one percent increase in GDP leads to increase green growth by 0.24, 0.26 and 0.32 percent for higher, upper-middle and lower middle-income countries in long run. The findings consistent with Iqbal et al. (2024). Renewable energy consumption (lnREC) also reported positive and significant impact in all three income groups. The renewable energy consumption has a universal importance but if we look the policy and investment in renewable are paying off particularly in higher income economies. Natural resource rent (lnNRR) coefficient value is 0.015 which is significant impact on green growth only in lower-middle income countries, while in higher income and upper middle-income economies the relationship is insignificant,

Table 3 Findings of the Cross-Sectional Dependence test.

Variable	CD-test	*p*-value	Corr	Abs(Corr)
lnGG	154.59	0.000	0.862	0.862
lnTI	42.29	0.000	0.236	0.620
lnGDP	152.08	0.000	0.848	0.848
lnNRR	38.73	0.000	0.216	0.370
lnREC	79.30	0.000	0.442	0.609
lnKOFGI	171.36	0.000	0.955	0.955

Table 4 Panel Unit Root test.

	LLC		IPS		CIPS		CADF	
Variable	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
lnGG	4.8167	−14.1075***	0.2167	−5.6811***	−1.891	−3.792***	−1.825	−5.225***
lnTI	0.1890	−10.6808***	−1.9464	−4.2552***	−2.004	−2.998***	−1.853	−4.122***
lnGDP	−3.8214***	−17.8966***	−0.6192	−4.6497***	−3.181***	−3.983***	−3.077***	−4.408***
lnREC	−3.0013***	−16.8060***	−1.5685	−5.3679***	−2.572***	−3.900***	−2.352***	−5.213***
lnNRR	0.6460	−18.8022***	−1.6593	−5.1598***	−2.024	−4.095***	−1.873	−5.340***
lnKOFGI	−19.6178***	−11.4233***	−5.1407***	−4.6250***	−2.459***	−3.910***	−2.929***	−5.300***

Table 5 Westerlund and Pedroni cointegration test.

Pedroni cointegration test			
Test Statistic	**Value**	***p*−value**	
Modified Phillips–Perron t	2.7258	0.0032	
Phillips–Perron t	−2.5531	0.0053	
Augmented Dickey–Fuller t	−1.6303	0.0515	
Westerlund cointegration test			
Statistic	Value	*Z*-value	*P*-value
Gt	−1.355	5.498	1.000
Ga	−3.765	6.875	1.000

Table 6 CS-ARDL outcomes.

Variables	**Coefficient**	**Std. Err.**	***Z***	***P* > |z|**
Long Run Estimates				
lnTI	0.0335	0.0157	2.13	0.033
lnGDP	0.3297	0.0470	7.02	0.000
lnREC	0.1585	0.0303	5.22	0.000
lnNRR	−0.0017	0.0043	−0.40	0.686
lnKOFGI	−0.0098	0.1263	−0.08	0.938
Short Run Estimates				
L(lnGG)	−0.8957	0.0321	−27.92	0.000
D(lnTI)	0.0671	0.0318	2.11	0.035
D(lnGDP)	0.6369	0.0921	6.91	0.000
D(lnNRR)	−0.0018	0.0083	−0.22	0.829
D(lnREC)	0.2990	0.0549	5.45	0.000
D(lnKOFGI)	−0.0378	0.2385	−0.16	0.874
ECM(−1)	−1.8957	0.0321	−59.09	0.000

Table 7 CS-ARDL Income Group.

Variable	**High income**	**Upper Middle income**	**Lower Middle income**
Long Run Estimates			
lnTI	0.0762 (0.0253)***	−0.0143 (0.0270)	0.0108 (0.0254)
lnGDP	0.2478 (0.0913)***	0.2626 (0.0186)***	0.3279 (0.1476)**
lnREC	0.1488 (0.0339)***	0.0965 (0.0149)***	0.1613 (0.0671)**
lnNRR	0.0060 (0.0078)	−0.0106 (0.0086)	0.0159 (0.0085)*
lnKOFGI	−0.1372 (0.1992)	−0.1439 (0.0862)*	0.0861 (0.1693)
Short Run Estimates			
L(lnGG)	−0.9686 (0.0591)***	−0.8597 (0.0486)***	(−0.8724 (0.0944)***
D(lnTI)	0.1481 (0.0513)***	−0.0257 (0.0509)	0.0273 (0.0435)
D(lnGDP)	0.5419 (0.1697)***	0.4892 (0.0382)***	0.6105 (0.2717)**
D(lnREC)	0.2906 (0.0644)***	0.1811 (0.0296)***	0.2930 (0.1164)**
D(lnNRR)	0.0130 (0.0153)	−0.0176 (0.0162)	0.0316 (0.0185)*
D(lnKOFGI)	−0.3237 (0.3777)	−0.2788 (0.1736)*	0.1692 (0.3344)
ECM(−1)	−1.9686 (0.0591)***	−1.8597 (0.0486)***	−1.8724 (0.0944)***

indicating that these economies are less resource dependance. The globalization variable which is weakly negative and significant (−0.143*) in upper middle-income economies while insignificant in high and lower-middle income economies in Europe.

Table 8 ARDL PMG.

Variable	**Coefficient**	**Std. Error**	***z***	***P*-value**
Long Run Estimates				
lnTI	−0.2845	0.0523	−5.44	0.000
lnGDP	0.3762	0.0745	5.05	0.000
lnNRR	−0.0594	0.0147	−4.05	0.000
lnREC	0.1477	0.0168	8.78	0.000
lnKOFGI	1.9313	0.2481	7.79	0.000
Short Run Estimates				
D(lnTI)	6128.761	6128.716	1.00	0.317
D(lnGDP)	0.4873	0.0526	9.26	0.000
D(lnNRR)	−0.0126	0.0072	−1.76	0.079
D(lnREC)	0.2994	0.0482	6.22	0.000
D(lnKOFGI)	0.1042	0.1129	0.92	0.356
C	−3465.47	3464.503	−1.00	0.317

Now in the short run the error correction mechanism (ECM) value is negative and significant in all income groups indicating that the system converges from short run to long run. In the short run green growth which is negative and highly significant in all income groups. The speed up adjustment is (−0.96***) fast in high income economies, and slightly slow in lower middle-income economies. Technological innovation is significant in high income economies (0.148***) showing that high income economies can immediately influence innovation for short run benefits while in other economies have insignificant results are reported. It indicating that due to delays or inefficiencies it will take time in convergence from short run to long run. Economic growth and Renewable energy consumption have positive and significant impact on the green growth of all income groups. Natural resource rent (lnNRR) is significantly only in the lower middle-income economies with coefficient value is (0.0316**) indicating that short run dependency on natural resources. Thus, the overall results indicating that some determents are important like GDP and renewable energy, while the effectiveness of other variables like innovation capabilities, globalization depends upon the countries institutional capabilities and income.

Interestingly, the results are quite consistent in the above conclusions. In Table 8, Pool Mean Group results indicates that in the long run, Gross Domestic Product, Globalization and Renewable energy consumption have a positive and statistically significant effect on the green growth of Europe, indicating that economic development, global integration and clean energy contribute to the sustainable development in the European economies over the time. On the other hand, technological innovation and natural resource rents have negative and significant impact on green growth. The reason is that may be in these economies' innovation may not be green-oriented which degrade the environment. Although in the short run Gross Domestic Product and REC have a positive and significant impact, while natural resource rents (lnNRR) have a significant but negative impact reported. Globalization and technological innovation have statistically insignificant impact on the short run, indicating that their effects will take time. Green growth is calculating this ratio involves dividing the GDP of a country by its energy-related CO2 emissions. The resulting value indicates how much economic value is being produced for each ton of CO2 emitted. This metric can help policymakers and analysts to evaluate the effectiveness of strategies aimed at decoupling Economic growth from carbon (CO2) emissions. Overall results indicating that short run mainly attentive on economic activity & renewable energy while long term dynamics highlighting the need for environmentally focused innovation & better resource management in these regions.

Conclusion and policy recommendations

This study provides a comprehensive empirical analysis to investigate the role and importance of Technological innovation and Renewable Energy consumption in promoting green growth or attaining sustainable development in European economies categorized into high income, upper middle income and lower middle-income groups. Using the Cross Sectional ARDL model on data spanning from 1990 to 2023, the findings of the study show that economic growth (GDP) is the important and consistent indicator of green growth in both the short and long run across all income groups. It indicates that higher income associated with improved environmental outcomes like better institutions, better infrastructure and higher investments in clean technologies. Technological innovation has a positive and significant impact on green growth in high-income European economies, probably due to stronger institutional frameworks, access to clean technologies and larger investment in environmentally friendly research and development. However, its effect in middle- and lower-income economies are statistically insignificant or negative, suggesting that in less developed economies, technological innovation may be either pollution-intensive or insufficiently oriented towards environmental sustainability. Similarly, the renewable energy consumption has also positive and statistically significant impact on green growth indicating that clean energy is the important indicator for achieving sustainable environmental goals.

These findings have several economic implications. First, they support the environmental Kuznets curve may hold in higher income economies of the Europe while less evident for low-income economies. Secondly, the divergence in the role of globalization and technological innovation across all income economies emphasizing the need for differentiated policy strategies that will handling the structural weakness and institutional capabilities of developing economies.

A practical example that validates the applicability of this study is the Germany's Energiewende which was a long-term strategic initiative aimed to shift Germany to a greener energy future. Germany has greatly invested in technological innovation, specifically in energy efficiency, smart grid and alternative energy sources like wind and solar power. These innovations have played a critical role in discontinuing the correlation between economic development and environmental deterioration, and Germany takes the lead among European green growth. The implications of this study, particularly on technological innovation and renewable energy in achieving sustainable development, are clearly evident in the German example.

Keeping in consideration this study's findings, the current study suggests that the policymakers especially middle- and lower-income economies should prioritize aligning technological innovation with environmental goals by supporting R&D, clean-tech startups and innovation incentives. Additionally, the positive role of renewable energy across all income groups highlights the importance of scaling up clean energy infrastructure and offering policy incentives like subsidies, tax breaks and feed-in tariffs. As far as renewable energy is concerned, government must prioritize substantial investment in renewable energy infrastructure and providing the above-mentioned incentives which can help to enhance the green growth outcomes. Due to globalization, economies should focus on strengthening the environmental standards that aligned with the sustainable objectives.

Furthermore, in the context of uncertainty like climate policy shifts, war, covid etc., rising uncertainties can harm the countries' efforts for sustainability (Ongan et al., (2025)). Therefore, it is recommended that European countries need to embrace adaptive green strategies. These encompass investments in resilient low-carbon technologies and the promotion of renewable energy using flexible incentives. Public-private partnerships and regional collaboration can facilitate optimal technological diffusion and ensure stable green growth with uncertain conditions.

However, there are some limitations to this study. First, although the CS-ARDL model is capable of modeling short- and long-run relationships, it makes homogeneity of long-run coefficients that might not completely capture unique country-specific dynamics. Second, data unavailability in certain countries can limit generalizability of findings. Future research can use other proxies for sustainable development, i.e., environmental quality indices or inclusive growth indicators instead of green growth. Moreover, nonlinear or country-specific models can be employed in future research to realize more heterogeneous effects. Finally, combining policy variables like environmental policy or innovation-friendly fiscal policy can further increase the explanatory power of the model as well as its practical relevance.

Data availability

Data will be available on request to the corresponding author.

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References

Acheampong AO, Boateng EB (2019) Modelling carbon emission intensity: application of artificial neural network. J Clean Prod 225:833–856. https://doi.org/10.1016/j.jclepro.2019.03.352

Ahmad M, Wu Y (2022) Combined role of green productivity growth, economic globalization, and eco-innovation in achieving ecological sustainability for OECD economies. J Environ Ment Manag 302:113980. https://doi.org/10.1016/j.jenvman.2021.113980

Ahmad N, Youjin L, Žiković S, Belyaeva Z (2023) The effects of technological innovation on sustainable development and environmental degradation: Evidence from China. Technol Soc 72:102184. https://doi.org/10.1016/j.techsoc.2022.102184

Akadiri SS, Alola AA, Bekun FV, Etokakpan MU (2020) Does electricity consumption and globalization increase pollutant emissions? Implications for environmental sustainability target for China. Environ Sci Pollut Res 27:25450–25460. https://doi.org/10.1007/s11356-020-08784-3

Akbar A, Gul A, Sohail M, Hedvicakova M, Haider SA, Ahmad S, Iqbal S (2024) Impact of renewable and non-renewable energy resources on CO2 emission: empirical evidence from SAARC. Int J Energy Econ Policy 14(1):141–149. https://doi.org/10.32479/ijeep.15049

Al-Mulali U, Sheau-Ting L, Ozturk I (2015) The global move toward Internet shopping and its influence on pollution: an empirical analysis. Environ Sci Pollut Res 22:9717–9727. https://doi.org/10.1007/s11356-015-4142-2

Alsagr N, Ozturk I (2024) Natural resources rent and green investment: does institutional quality matter? Resour Policy 90:104709. https://doi.org/10.1016/j.resourpol.2024.104709

Anwar MA, Zhang Q, Asmi F, Hussain N, Plantinga A, Zafar MW, Sinha A (2022) Global perspectives on environmental Kuznets curve: a bibliometric review. Gondwana Res 103:135–145. https://doi.org/10.1016/j.gr.2021.11.010

Apergis N, Ozturk I (2015) Testing environmental Kuznets curve hypothesis in Asian countries. Ecol Indic 52:16–22. https://doi.org/10.1016/j.ecolind.2014.11.026

Apergis N, Payne JE (2010) Renewable energy consumption and economic growth: evidence from a panel of OECD countries. Energy policy 38(1):656–660002. https://doi.org/10.1016/j.enpol.2009.09.002

Azam M, Hunjra AI, Taskin D, Al-Faryan MAS (2023) Role of ethnic conflicts, regularization and natural resource abundance in sustainable development. Resour Policy 85:103936. https://doi.org/10.1016/j.resourpol.2023.103936

Bai X, Wang KT, Tran TK, Sadiq M, Trung LM, Khudoykulov K (2022) Measuring China's green economic recovery and energy environment sustainability: econometric analysis of sustainable development goals. Econ Anal Policy 75:768–779. https://doi.org/10.1016/j.eap.2022.07.005

Banerjee A, Dolado J, Mestre R (1998) Error-correction mechanism tests for cointegration in a single-equation framework. J time Ser Anal 19:267–283. https://doi.org/10.1111/1467-9892.00091

Bekhet HA, Latif NWA (2018) The impact of technological innovation and governance institution quality on Malaysia's sustainable growth: Evidence from a dynamic relationship. Technol Soc 54:27–40. https://doi.org/10.1016/j.techsoc.2018.01.014

Bayer C, Hanck C (2013) Combining non-cointegration tests. J Time Ser Anal 34(1):83–95. https://doi.org/10.1111/j.1467-9892.2012.00814.x

Bekun FV, Yalçiner K, Etokakpan MU, Alola AA (2020) Renewed evidence of environmental sustainability from globalization and energy consumption over economic growth in China. Environ Sci Pollut Res 27:29644–29658. https://doi.org/10.1007/s11356-020-08866-2

Bertheau P (2020) Assessing the impact of renewable energy on local development and the sustainable development goals: insights from a small Philippine island. Technol Forecast Soc Change 153:119919. https://doi.org/10.1016/j.techfore.2020.119919

Bhattacharyya S, Hodler R (2010) Natural resources, democracy and corruption. Eur Econ Rev 54(4):608–621. https://doi.org/10.1016/j.euroecorev.2009.10.004

Boswijk HP (1994) Testing for an unstable root in conditional and structural error correction models. J Econ 63:37–60. https://doi.org/10.1016/0304-4076(93)01560-9

Boubaker S, Omri A (2022) How does renewable energy contribute to the growth versus environment debate? Resour Policy 79:103045. https://doi.org/10.1016/j.resourpol.2022.103045

Breitung J, Candelon B (2006) Testing for short-and long-run causality: a frequency-domain approach. J Econ 132(2):363–378. https://doi.org/10.1016/j.jeconom.2005.02.004

Caglar AE (2020) The importance of renewable energy consumption and FDI inflows in reducing environmental degradation: bootstrap ARDL bound test in selected 9 countries. J Clean Prod 264:121663. https://doi.org/10.1016/j.jclepro.2020.121663

Cerqueira PA, Soukiazis E, Proença S (2021) Assessing the linkages between recycling, renewable energy and sustainable development: evidence from the OECD countries. Environ Dev Sustain 23(7):9766–9791. https://doi.org/10.1007/s10668-020-00780-4

Cheng X, Chen J, Jiang S, Dai Y, Zeng J, Shuai C, Liu G (2021) Pursuing sustainable development goals: a review of renewable energy and poverty alleviation nexus. Environ Dev 40:100679. https://doi.org/10.1016/j.envdev.2021.100679

Chien F (2022) How renewable energy and non-renewable energy affect environmental excellence in N-11 economies? Renew Energy 196:526–534. https://doi.org/10.1016/j.renene.2022.07.013

Choudhury T, Kayani UN, Gul A, Haider SA, Ahmad S (2023) Carbon emissions, environmental distortions, and impact on growth. Energy Econ 126:107040. https://doi.org/10.1016/j.eneco.2023.107040

Christmann P, Taylor G (2001) Globalization and the environment: determinants of firm self-regulation in China. J Int Bus Stud 32:439–458. https://doi.org/10.1057/palgrave.jibs.8490976

Chudik A, Pesaran MH (2015) Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. J Econ 188(2):393–420. https://doi.org/10.1016/j.jeconom.2015.03.007

Constantinescu A, Frone S (2014) The role of technological innovation in sustainable economic development

Dinda S (2004) Environmental Kuznets curve hypothesis: a survey. Ecol Econ 49(4):431–455. https://doi.org/10.1016/j.ecolecon.2004.02.011

Engle RF, Granger CWJ (1987) Co-integration and error correction: representation, estimation, and testing. Econometrica 55:251–276. https://doi.org/10.2307/1913236

Erdogan S (2024) On the impact of natural resources on environmental sustainability in African countries: a comparative approach based on the EKC and LCC hypotheses. Resour Policy 88:104492. https://doi.org/10.1016/j.resourpol.2023.104492

Fokkema J, Jansen L, Mulder K (2005) Sustainability: necessity for a prosperous society. Int J Sustain High Educ 6(3):219–228. https://doi.org/10.1108/14676370510607197

Franceschini S, Pansera M (2015) Beyond unsustainable eco-innovation: the role of narratives in the evolution of the lighting sector. Technol Forecast Soc Change 92:69–83. https://doi.org/10.1016/j.techfore.2014.11.007

Fu R, Liu J (2023) Revenue sources of natural resources rents and its impact on sustainable development: evidence from global data. Resour Policy 80:103226. https://doi.org/10.1016/j.resourpol.2022.103226

Geweke J (1982) Measurement of linear dependence and feedback between multiple time series. J Am Stat Assoc 77(378):304–313. https://doi.org/10.1080/01621459.1982.10477803

Grossman GM, Krueger AB (1991) Environmental impacts of a North American free trade agreement. B) Panayotou, T. (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development. https://doi.org/10.3386/w3914

Güney T (2019) Renewable energy, non-renewable energy and sustainable development. Int J Sustain Dev World Ecol 26(5):389–397. https://doi.org/10.1080/13504509.2019.1595214

Hansen BE (1995) Rethinking the univariate approach to unit root testing: Using covariates to increase power. Econ Theory 11(5):1148–1171. https://doi.org/10.1017/S0266466600009993

Hassan YA, Abubakar A (2025) Umar Auwal. J Econ Allied Res (JEAR), 454

Hatemi-j A (2008) Tests for cointegration with two unknown regime shifts with an application to financial market integration. Empir Econ 35(3):497–505. https://doi.org/10.1007/s00181-007-0175-9

He J, Yang Y, Liao Z, Xu A, Fang K (2022) Linking SDG 7 to assess the renewable energy footprint of nations by 2030. Appl Energy 317:119167. https://doi.org/10.1016/j.apenergy.2022.119167

Horbach J, Rammer C, Rennings K (2012) Determinants of eco-innovations by type of environmental impact—the role of regulatory push/pull, technology push and market pull. Ecol Econ 78:112–122. https://doi.org/10.1016/j.ecolecon.2012.04.005

Hosoya Y (1991) The decomposition and measurement of the interdependency between second-order stationary processes. Probab theory Relat fields 88(4):429–444. https://doi.org/10.1007/BF01192551

Hübler Michael et al. (2012) An integrated assessment model with endogenous growth. Ecol Econ 83:118–131. https://doi.org/10.1016/j.ecolecon.2012.07.014

Im KS, Pesaran MH, Shin Y (2003) Testing for unit roots in heterogeneous panels. J Econ 115(1):53–74. https://doi.org/10.1016/S0304-4076(03)00092-7

Iqbal K, Hassan ST, Geng Y, Cai C (2024) Impact of Green Technological Innovations, ICT, and Renewable Energy on CO2 Emissions in Emerging Economies. International Journal of Energy Research 2024(1):5594324

Işık C, Ongan S, Islam H, Menegaki AN (2024) A roadmap for sustainable global supply chain distribution: exploring the interplay of ECON-ESG factors, technological advancement and SDGs on natural resources. Resour Policy 95:105114. https://doi.org/10.1016/j.resourpol.2024.105114

Işık C, Ongan S, Islam H, Balsalobre-Lorente D, Sharif A (2024) ECON-ESG factors on energy efficiency: Fostering sustainable development in ECON-growth-paradox countries. Gondwana Res 135:103–115. https://doi.org/10.1016/j.gr.2024.07.020

Jebli MB, Youssef SB, Ozturk I (2016) Testing environmental Kuznets curve hypothesis: the role of renewable and non-renewable energy consumption and trade in OECD countries. Ecol Indic 60:824–831. https://doi.org/10.1016/j.ecolind.2015.08.031

Ji X, Song T, Umar M, Safi A (2023) How China is mitigating resource curse through infrastructural development? Resour Policy 82:103590. https://doi.org/10.1016/j.resourpol.2023.103590

Johansen S (1991) Estimation and hypothesis testing of cointegration vectors in Gaussian Vector Autoregressive Models. Econometrica 59:1551–1580. https://doi.org/10.2307/2938278

Khan I, Mahmood T, Ahmad S, Shil NC (2025) Factors impacting sustainable development in selected South Asian Economies: empirical evidence. Sustain Futures 9:100557. https://doi.org/10.1016/j.sftr.2025.100557

Khan Z, Ali S, Umar M, Kirikkaleli D, Jiao Z (2020) Consumption-based carbon emissions and international trade in G7 countries: the role of environmental innovation and renewable energy. Sci Total Environ 730:138945. https://doi.org/10.1016/j.scitotenv.2020.138945

Kuznets S (1955) Economic Growth and Income Inequality. The American Economic Review 45(1):1–28

Kwilinski A, Dacko-Pikiewicz Z, Szczepanska-Woszczyna K, Lyulyov O, Pimonenko T (2025) The role of innovation in the transition to a green economy: a path to sustainable growth. J Open Innov: Technol, Mark, Complex 11(2):100530. https://doi.org/10.1016/j.joitmc.2025.100530

Levin A, Lin CF, Chu CSJ (2002) Unit root tests in panel data: asymptotic and finite-sample properties. J Econ 108(1):1–24. https://doi.org/10.1016/S0304-4076(01)00098-7

Li Q, Cherian J, Shabbir MS, Sial MS, Li J, Mester I, Badulescu A (2021) Exploring the relationship between renewable energy sources and economic growth. The case of SAARC countries. Energies 14(3):520. https://doi.org/10.3390/en14030520

Liu F, Su CW, Qin M, Umar M (2023) Is renewable energy a path towards sustainable development? Sustain Dev 31(5):3869–3880. https://doi.org/10.1002/sd.2631

Liu X, Udemba EN, Emir F, Hussain S, Khan NU, Abdallah I (2024) Nexus between resource policy, renewable energy policy and export diversification: asymmetric study of environment quality towards sustainable development. Resour Policy 88:104402. https://doi.org/10.1016/j.resourpol.2023.104402

Lyeonov S, Pimonenko T, Bilan Y, Štreimikienė D, Mentel G (2019) Assessment of green investments' impact on sustainable development: Linking gross domestic product per capita, greenhouse gas emissions and renewable energy. Energies 12(20):3891. https://doi.org/10.3390/en12203891

Maki D (2012) Tests for cointegration allowing for an unknown number of breaks. Econ Model 29(5):2011–2015. https://doi.org/10.1016/j.econmod.2012.04.022

Manderson E, Kneller R (2012) Environmental regulations, outward FDI and heterogeneous firms: are countries used as pollution havens? Environ Resour Econ 51:317–352. https://doi.org/10.1007/s10640-011-9500-z

Marco-Lajara B, Martínez-Falcó J, Sánchez-García E, Millan-Tudela LA (2023) Analyzing the role of renewable energy in meeting the sustainable development goals: A bibliometric analysis. Energies 16(7):3137. https://doi.org/10.3390/en16073137

Moslehpour M, Aldeehani TM, Sibghatullah A, Duc Tai T, Hien Phan TT, Quang Ngo T (2023) Dynamic association between technological advancement, green finance, energy efficiency and sustainable development: evidence from Vietnam. Economic research-Ekonomska istraživanja, 36(3). https://doi.org/10.1080/1331677X.2023.2190796
Nosheen M, Akbar A, Sohail M, Iqbal J, Hedvicakova M, Ahmad S, Gul A (2024) From fossil to future: the transformative role of renewable energy in shaping economic landscapes. Int J Energy Econ Policy 14(4):606–615. https://doi.org/10.32479/ijeep.16006
Omri A (2020) Technological innovation and sustainable development: does the stage of development matter? Environ Impact Assess Rev 83:106398. https://doi.org/10.1016/j.eiar.2020.106398
Omri A, Nguyen DK (2014) On the determinants of renewable energy consumption: international evidence. Energy 72:554–560. https://doi.org/10.1016/j.energy.2014.05.081
Ongan S, Gocer I, Işık C (2025) Introducing the New ESG-Based Sustainability Uncertainty Index (ESGUI). *Sustainable Development*. https://doi.org/10.1002/sd.3351
Paredis E (2011) Sustainability transitions and the nature of technology. Found Sci 16:195–225. https://doi.org/10.1007/s10699-010-9197-4
Park JY (1992) Canonical cointegrating regressions. Econometrica: Journal of the Econometric Society, 119-143. https://doi.org/10.2307/2951679
Pedroni P (1999) Critical values for cointegration tests in heterogeneous panels with multiple regressors. Oxf Bull Econ Stat 61(S1):653–670. https://doi.org/10.1111/1468-0084.0610s1653
Pedroni P (2004) Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. Econ Theory 20(3):597–625
Pesaran MH (2004) General diagnostic tests for cross section dependence in panels. Camb Working Pap Econ 1240(1):1. https://doi.org/10.17863/CAM.5113
Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. J Appl Econ 22(2):265–312. https://doi.org/10.1002/jae.951
Pesaran MH, Shin Y, Smith RP (1999) Pooled mean group estimation of dynamic heterogeneous panels. J Am Stat Assoc 94(446):621–634. https://doi.org/10.1080/01621459.1999.10474156
Phillips PC, Hansen BE (1990) Statistical inference in instrumental variables regression with I(1) processes. Rev Econ Stud 57(1):99–125. https://doi.org/10.2307/2297545
Popp D (2010) Innovation and climate policy. Annu Rev Resour Econ 2(1):275–298. https://doi.org/10.1146/annurev.resource.012809.103929
Porter M, Van der Linde C (1995) Green and competitive: ending the stalemate. Dyn Eco-Effic economy: Environ Regul Compet Advant 33:120–134. https://doi.org/10.1257/jep.9.4.97
Romer PM (1990) Endogenous technological change. J Polit Econ 98(5, Part 2):S71–S102. http://www.jstor.org/stable/2937632?origin=JSTOR-pdf
Sachs JD, Warner AM (2001) The curse of natural resources. Eur Econ Rev 45(4-6):827–838. https://doi.org/10.1016/S0014-2921(01)00125-8
Sadiq M, Moslehpour M, Qiu R, Hieu VM, Duong KD, Ngo TQ (2023) Sharing economy benefits and sustainable development goals: empirical evidence from the transportation industry of Vietnam. J Innov Knowl 8(1):100290. https://doi.org/10.1016/j.jik.2022.100290
Sadiq M, Ngo TQ, Pantamee AA, Khudoykulov K, Ngan TT, Tan LP (2023) The role of environmental social and governance in achieving sustainable development goals: evidence from ASEAN countries. Econ Res Ekonomska istraživanja 36(1):170–190. https://doi.org/10.1080/1331677X.2022.2072357
Saikkonen P (1992) Estimation and testing of cointegrated systems by an autoregressive approximation. Econom theory 8(1):1–27. https://doi.org/10.1017/S0266466600010720
Saleem H, Khan MB, Mahdavian SM (2022) The role of green growth, green financing, and eco-friendly technology in achieving environmental quality: evidence from selected Asian economies. Environ Sci Pollut Res 29(38):57720–57739. https://doi.org/10.1007/s11356-022-19799-3
Schwerhoff G, Sy M (2017) Financing renewable energy in Africa–Key challenge of the sustainable development goals. Renew Sustain Energy Rev 75:393–401. https://doi.org/10.1016/j.rser.2016.11.004
Shahbaz M, Shahzad SJH, Mahalik MK, Hammoudeh S (2018) Does globalisation worsen environmental quality in developed economies? Environ Modeling Assess 23:141–156. https://doi.org/10.1007/s10666-017-9574-2
Shao QG, Jiang CC, Lo HW, Liou JJ (2023) Establishing a sustainable development assessment framework for a smart city using a hybrid Z-fuzzy-based decision-making approach. Clean Technol Environ Policy 25(9):3027–3044. https://doi.org/10.1007/s10098-023-02547-7
Sharpley R (2020) Tourism, sustainable development and the theoretical divide: 20 years on. J Sustain Tour 28(11):1932–1946. https://doi.org/10.1080/09669582.2020.1779732
Silvestre BS, Ţîrcă DM (2019) Innovations for sustainable development: moving toward a sustainable future. J Clean Prod 208:325–332. https://doi.org/10.1016/j.jclepro.2018.09.244
Stern DI (2004) The rise and fall of the environmental Kuznets curve. World Dev 32(8):1419–1439. https://doi.org/10.1016/j.worlddev.2004.03.004
Stock JH, Watson MW (1993) A simple estimator of cointegrating vectors in higher order integrated systems. Econometrica: J Econ Soc, 783-820. https://doi.org/10.2307/2951763
Su CW, Naqvi B, Shao XF, Li JP, Jiao Z (2020) Trade and technological innovation: the catalysts for climate change and way forward for COP21. J Environ Manag 269:110774. https://doi.org/10.1016/j.jenvman.2020.110774
Sueyoshi T, Mo F, Wang DD (2022) Sustainable development of countries all over the world and the impact of renewable energy. Renew Energy 184:320–331. https://doi.org/10.1016/j.renene.2021.11.015
Suki NM, Suki NM, Afshan S, Sharif A, Meo MS (2022) The paradigms of technological innovation and renewables as a panacea for sustainable development: a pathway of going green. Renew Energy 181:1431–1439. https://doi.org/10.1016/j.renene.2021.09.121
Sun Y, Gao P, Tian W, Guan W (2023) Green innovation for resource efficiency and sustainability: empirical analysis and policy. Resour Policy 81:103369. https://doi.org/10.1016/j.resourpol.2023.103369
Tanner AN, Faria L, Moro MA, Iversen E, Østergaard CR, Park EK (2019) regional distribution of green growth patents in four Nordic countries: Denmark, Finland, Norway and Sweden. DTU, Department of Management Engineering: Lyngby
Udemba EN, Alola AA (2022) Asymmetric inference of carbon neutrality and energy transition policy in Australia: The (de) merit of foreign direct investment. J Clean Prod 343:131023. https://doi.org/10.1016/j.jclepro.2022.131023
Udemba EN, Yalçıntaş S (2021) Interacting force of foreign direct invest (FDI), natural resource and economic growth in determining environmental performance: A nonlinear autoregressive distributed lag (NARDL) approach. Resour Policy 73:102168. https://doi.org/10.1016/j.resourpol.2021.102168
Udemba EN, Rahman MM, Ekwueme D, Philips L (2024) Pathway to achieving carbon goal: Insight from interaction of export diversification, renewable energy, innovation, and financial policy. Environ Dev Sustain 26(5):11603–11621. https://doi.org/10.1007/s10668-023-03429-0
Ulucak R, Khan SUD (2020) Determinants of the ecological footprint: role of renewable energy, natural resources, and urbanization. Sustain Cities Soc 54:101996. https://doi.org/10.1016/j.scs.2019.101996
Umar M, Ji X, Kirikkaleli D, Shahbaz M, Zhou X (2020) Environmental cost of natural resources utilization and economic growth: can China shift some burden through globalization for sustainable development? Sustain Dev 28(6):1678–1688. https://doi.org/10.1002/sd.2116
Van der Ploeg F, Venables AJ (2011) Harnessing windfall revenues: optimal policies for resource-rich developing economies. Econ J 121(551):1–30. https://doi.org/10.1111/j.1468-0297.2010.02411.x
Vasylieva T, Lyulyov O, Bilan Y, Streimikiene D (2019) Sustainable economic development and greenhouse gas emissions: The dynamic impact of renewable energy consumption, GDP, and corruption. Energies 12(17):3289. https://doi.org/10.3390/en12173289
Wang G, Sadiq M, Bashir T, Jain V, Ali SA, Shabbir MS (2022) The dynamic association between different strategies of renewable energy sources and sustainable economic growth under SDGs. Energy Strategy Rev 42:100886. https://doi.org/10.1016/j.esr.2022.100886
Wang S, Zhu J, Wang L, Zhong S (2022) The inhibitory effect of agricultural fiscal expenditure on agricultural green total factor productivity. Sci Rep. 12(1):20933
Westerlund J (2005) New simple tests for panel cointegration. Econ Rev 24(3):297–316. https://doi.org/10.1080/07474930500243019
Xu J, Zhao J, She S, Liu W (2022) Green growth, natural resources and sustainable development: evidence from BRICS economies. Resour Policy 79:103032. https://doi.org/10.1016/j.resourpol.2022.103032
Xu Z, Baloch MA, Danish K, Meng F, Zhang J, Mahmood Z (2018) Nexus between financial development and CO2 emissions in Saudi Arabia: analyzing the role of globalization. Environ Sci Pollut Res 25:28378–28390. https://doi.org/10.1007/s11356-018-2876-3
Yikun Z, Gul A, Saleem S, Shabbir MS, Bilal K, Abbasi HM (2021) The relationship between renewable energy sources and sustainable economic growth: evidence from SAARC countries. Environ Sci Pollut Res 28:33390–33399. https://doi.org/10.1007/s11356-021-12795-z
Yu L, Gao X, Lyu J, Feng Y, Zhang S, Andlib Z (2023) Green growth and environmental sustainability in China: the role of environmental taxes. Environ Sci Pollut Res 30(9):22702–22711. https://doi.org/10.1007/s11356-022-23355-4
Yuan B, Zhang Y (2020) Flexible environmental policy, technological innovation and sustainable development of China's industry: the moderating effect of environment regulatory enforcement. J Clean Prod 243:118543. https://doi.org/10.1016/j.jclepro.2019.118543
Zhang Y, Mao Y, Jiao L, Shuai C, Zhang H (2021) Eco-efficiency, eco-technology innovation and eco-well-being performance to improve global sustainable development. Environ Impact Assess Rev 89:106580. https://doi.org/10.1016/j.eiar.2021.106580

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