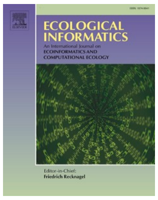
Ecological Informatics 87 (2025) 103093

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf



Towards eco-efficiency of OECD countries: How does environmental governance restrain the destructive ecological effect of the excess use of natural resources?

Brahim Bergougui [a,b,c,*,1], Elma Satrovic [d,1]

[a] International Institute of Social Studies (ISS), Erasmus University Rotterdam, Hague, the Netherlands
[b] College of Business & Economics, Qatar University, Doha, Qatar
[c] National Higher School of Statistics and Applied Economics (ENSSEA), Koléa, Algeria
[d] Department of International Trade and Logistics, Faculty of Economics, Administrative and Social Sciences, Hasan Kalyoncu University, Gaziantep, Türkiye

ARTICLE INFO

Keywords:
Excess use of natural resources
Environmental governance
Overall eco-efficiency
Services eco-efficiency
OECD

ABSTRACT

Developed economies face mounting environmental challenges from excessive resource consumption, but we lack clear evidence on how environmental policies can best address these issues. This study investigates how environmental governance shapes resource use and ecological efficiency across nine OECD countries from 1997 to 2020. Our analysis reveals that stronger environmental policies significantly improve eco-efficiency: a 1 % increase in environmental governance effectiveness enhances eco-efficiency by 0.65–0.95 %, with the strongest effects observed in countries currently showing lower ecological efficiency. We find that increasing energy transition efforts and research and development investment each contribute to improved eco-efficiency (0.07–0.11 % and 0.19–0.35 % respectively), while excessive resource use reduces it by 0.07–0.03 %. Notably, our study introduces a novel analytical approach by examining how environmental policies moderate the negative impacts of resource overuse across different levels of ecological efficiency. This relationship proves especially important for countries struggling with lower eco-efficiency, where strong environmental governance can effectively offset the harmful effects of excessive resource consumption. These findings remain consistent across multiple measures of eco-efficiency and trade indicators, offering robust evidence for policymakers. Our research provides practical guidance for balancing economic development with environmental protection through targeted policy interventions, particularly in resource-intensive economies working to improve their ecological performance.

1. Introduction

Over the past decades, Organisation for Economic Co-operation and Development (OECD) countries have achieved substantial economic growth and development through a complex interplay of resource utilization and environmental considerations. This expansion is primarily rooted in the countries' rich reserves of minerals, energy sources, and fertile lands, often leading to an excess use of natural resources (EUM) (OECD, 2009). The historical trajectory of OECD nations reveals a nuanced narrative of economic progress that has increasingly confronted the ecological implications of intensive development. The economic growth in these countries has been paralleled by a growing recognition of environmental concerns, prompting a comprehensive assessment of their eco-efficiency and sustainability over the long term

---

Abbreviations: DI, Import Diversification Index; EIT, Economic Importance of International Trade; EPS, Environmental Policy Stringency; ETG, Environmental Governance (Environmental Policy Stringency Index); EUM, Excess Use of Natural Resources; LEUM, Log of Excess Use of Natural Resources; LPRO, Log of GDP per capita; LSEE, Log of Services Eco-Efficiency; LTEE, Log of Total Eco-Efficiency; LTRA, Log of Energy Transition; MACS, Moment Quantile Regression; OECD, Organisation for Economic Co-operation and Development; PRO, Gross Domestic Product (GDP) per capita; RD, Research and Development intensity; RESR, Natural Resources Rents; SEE, Services Eco-Efficiency; SVL, Services Value Added (used for Services Eco-Efficiency); TEE, Total Eco-Efficiency; TRA, Energy Transition; TRD, Trade as a percentage of GDP; TRD, Trade (% of GDP); WB, World Bank.

[*] Corresponding author at: International Institute of Social Studies (ISS), Erasmus University Rotterdam, Hague, the Netherlands.
E-mail addresses: bergougui@iss.nl (B. Bergougui), elma.satrovic@hku.edu.tr (E. Satrovic).

[1] Co-authors.

https://doi.org/10.1016/j.ecoinf.2025.103093
Received 28 October 2024; Received in revised form 23 February 2025; Accepted 23 February 2025

(OECD, 2024). This evolving perspective represents a significant shift from earlier development models that prioritized economic expansion at the expense of environmental integrity. Regarding environmental performance, OECD countries generally rank higher than developing nations, but there is still considerable variation within the group. According to the environmental performance index in 2024, many OECD countries rank in the top 20 out of 180 countries, with scores ranging from 60 to 80 out of 100, as shown in Fig. 1. However, some OECD members still struggle with environmental issues, particularly related to greenhouse gas emissions and air quality. The OECD has stressed the importance of transitioning to a green economy to boost economic growth while respecting environmental carrying capacity (OECD, 2019). The old paradigm of sacrificing the environment for economic growth, often associated with EUM, is increasingly seen as outdated within these countries (Yıldız, 2023). This shift represents a fundamental reconceptualization of economic development, moving beyond traditional extractive models to more sustainable approaches. Transitioning the economic and social development model towards a green economy has emerged as a top priority for many OECD nations. This shift reflects the growing emphasis on sustainability and the need to balance economic growth with environmental preservation (Doğan et al., 2025). Green development initiatives have spread across industries as part of this ecological approach (Mamghaderi et al., 2023).

The fundamental basis of the complex interaction between economic growth and environmental conservation is the significant correlation between a given area's propensity for EUM and its influence on eco-efficiency (Le et al., 2020). The excess use of minerals, forests, water bodies, and fertile landforms the cornerstone of economic activity and contributes to societal well-being in OECD nations. However, this very excess that drives economic progress also introduces challenges related to maintaining ecological balance, adopting sustainable resource management practices, and adhering to environmental regulations (Chang et al., 2024). Several OECD countries have faced what is known as the "resource curse," where EUM does not always lead to improved economic performance and can even harm eco-efficiency (Bergougui and Murshed, 2020, 2021, 2023; Liu et al., 2023; OECD, 2009). Eco-efficiency, as explained by and Bergougui (2024a) and Sun and Gao (2023a), refers to how effectively ecological systems transform energy and materials into biomass and other useful outputs. In the context of managing EUM within OECD countries, eco-efficiency often serves as a benchmark for assessing sustainable resource use (OECD, 2015). The relationship between EUM and eco-efficiency has been studied across various OECD settings. While some research indicates that regions prone to EUM suffer from reduced eco-efficiency, other studies, such as (Guo et al., 2024), argue that with technological advancements and sound governance, areas experiencing EUM can achieve higher levels of eco-efficiency. The environmental policy stringency (EPS) is profound in OECD member countries and plays a crucial role in driving modern economic growth and managing EUM. EPS has become essential for the transition to a green economy and is vital for environmental protection and avoiding future ecological disasters, significantly impacting these countries' overall economic progress and eco-efficiency (Sohag et al., 2024). EPS in OECD countries encompasses both market and non-market-based approaches. Market-based policies include taxes on economic externalities, such as carbon emissions taxes, emissions-relevant trading strategies, and deposit-refund procedures. Non-market-based environmental policies consist of command-and-control tactics, including enforcement and compliance measures. The prime objectives of the EPS are to address market failure, manage EUM, and galvanize sustainable economic development. EPS in OECD countries focus on mitigation policies, mainly promoting renewable/clean energies and energy efficiency through technological development. Environmental policies play a crucial role in moderating the impact of EUM on ecological efficiency, as highlighted by Sun et al. (2021). Their research suggests that well-designed policies can mitigate the negative effects of EUM and promote the integration of sustainable practices.

The literature indicates that the primary objective of eco-efficiency is to optimize economic productivity while reducing environmental impact and resource consumption (Fang et al., 2024). In OECD countries, eco-efficiency research has increasingly shifted from focusing solely on economic production to encompassing social services. Furthermore, there has been a transition from using two-dimensional resource and environmental metrics to incorporating three-dimensional indicators that account for economic, social, and environmental factors (OECD, 2008). However, assessments of human productivity have often ignored fundamental aspects of human flourishing (Akpanke et al., 2024). While OECD countries generally maintain higher living standards compared to developing nations, balancing rapid economic and social development with environmental protection and managing EUM remains a challenge. The ecological economic system in these countries increasingly uses stage indicators, whereas GDP is still widely used as a final output by researchers (Chen et al., 2022; Yıldız, 2024). Though improving human well-being is a key goal of sustainable development in OECD countries, there remains a persistent challenge in ensuring that environmental protection measures and efforts to curb EUM do not adversely affect the quality of life of citizens. Balancing sustainability with maintaining high living standards continues to be a critical concern.

The primary objective of this study is to examine how environmental governance moderates the ecological impact of excessive natural resource use on eco-efficiency across OECD countries. Specifically, the research aims to investigate the interplay between environmental policies, energy transition, research and development, and international trade in driving eco-efficiency and achieving sustainable resource

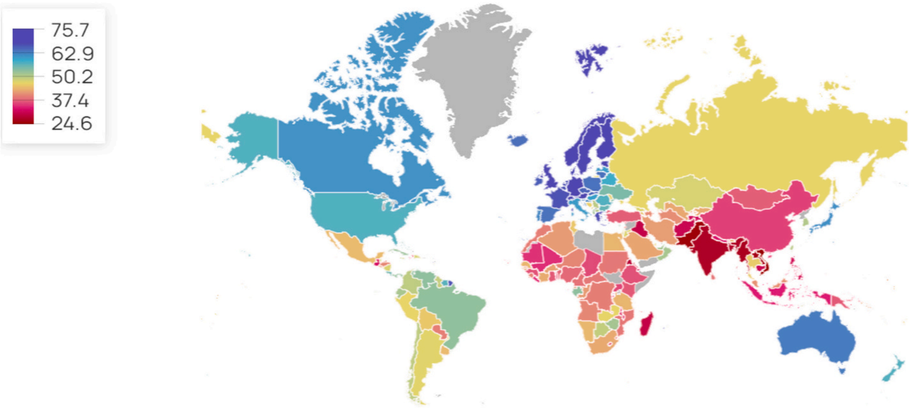


Fig. 1. Overall environmental performance index scores for 180 countries in 2024.
Source: Yale Center for Environmental Law and Policy.

management over the period 1997–2020. This objective is further delineated through the following key questions.

- How does the excessive use of natural resources influence eco-efficiency in OECD countries?
- What roles do energy transition, research and development, and international trade play in enhancing eco-efficiency?
- How does environmental governance moderate the negative ecological effects of excessive use of natural resources on eco-efficiency, particularly in countries with lower eco-efficiency levels?
- To what extent can alternative eco-efficiency indicators and different proxies for international trade validate the robustness of the findings?

The novelty of this paper lies in its comprehensive examination of the relationship between natural resource use, eco-efficiency, and environmental governance in nine OECD countries over the period 1997–2020. This study makes several key contributions to the literature:

- The paper addresses a significant gap in the existing literature by investigating how effective environmental governance can mitigate the negative ecological impacts of EUM, a topic that has been underexplored in prior studies.
- The study employs moment quantile regression (MACS), offering a unique methodological approach that allows for a more nuanced understanding of how variables like energy transition TRA, RD, and international trade affect eco-efficiency across different quantiles of the distribution. This approach provides deeper insights than traditional methods, particularly in capturing heterogeneity in eco-efficiency across countries.
- The research highlights the moderating role of ETG in mitigating the detrimental effects of EUM on eco-efficiency. This is particularly important for countries with lower eco-efficiency, where ETG has a more pronounced positive effect.
- By incorporating robustness analyses, such as an alternative eco-efficiency indicator (services eco-efficiency), and using different proxies for international trade (import diversification index - DI), the paper enhances the validity of its findings and contributes a broader understanding of the dynamics influencing eco-efficiency.

The rest of the paper is organized as follows. The second section offers a theoretical analysis of the relationship between natural resource use, eco-efficiency, and environmental governance, while also outlining the empirical methodology, including the use of MACS, and detailing the data sources and variables used. The third section presents the empirical results, followed by an in-depth discussion. The final section concludes with the implications of the findings and offers recommendations for policy and future research.

2. Literature review

This section carries out a comprehensive assessment of the empirical literature and theoretical background on the interplay among natural resources, environmental governances, and eco-efficiency. To facilitate a structured analysis, we have categorized the literature into the following subsections:

2.1. Natural resources and eco-efficiency

The perception of sustainable growth emphasizes achieving economic objectives while simultaneously preserving environmental and social well-being. A critical facet of sustainable development lies in the responsible management and use of natural resources. Effective natural resource management plays a pivotal role in reducing ecological footprints and fostering environmental stability (Kongbuamai et al., 2020). Excessive energy consumption, however, depletes natural resources, impedes economic progress, and exacerbates environmental challenges. To address these issues, sustainable natural resource management is essential to optimize resource use and alleviate resource constraint (Olawumi and Chan, 2018). Ahmad et al. (2020) examined how natural resources influence environmental degradation in 22 emerging economies, revealing that natural resources impact ecological footprints. However, the study also highlighted that advanced technologies could restore natural resources and enhance ecological resilience. Erdoğan et al. (2021) investigated the position of natural resources in ecological footprints across African countries from 1980 to 2016. Their findings indicated that inefficient resource utilization and poor environmental governance significantly contributed to ecological footprints. In the case of China, He et al. (2022) demonstrated that oil revenues positively influence environmental sustainability by mitigating greenhouse gas emissions. Conversely, natural resource rents found to intensify greenhouse gas emissions, presenting a dual challenge for sustainability. Xiaoman et al. (2021) analyzed the impact of natural resource on environmental quality in Middle Eastern and North African (MENA) countries. While natural resources was found to improve environmental quality, trade openness, urbanization and economic growth negatively impacted ecological sustainability. Dong et al. (2018) investigated the interaction between China's carbon emissions and renewable energy, concluding that increased use of renewable energy and natural gas enhances environmental quality. Similarly, Umar et al. (2020) identified key determinants of emissions, such as globalization and natural resource use, and found that China's economic expansion often extends at the cost of environmental sustainability. Their study provided evidence that natural resource exploitation positively correlates with CO2 emissions and called for policy interventions to balance growth with environmental sustainability. Alfalih and Hadj (2022) used a Markov Regime Switching model to examine the natural resource-environmental sustainability links in Saudi Arabia. They found that natural resource sustains sustainability under both maximal and minimal environmental sustainability regimes. Similarly, Ali et al. (2022a) assessed the dynamics between remittances, natural resource, and economic expansion in Pakistan. They revealed that while resource extraction and economic expansion negatively affected environmental quality, the role of technological innovation remained ambiguous. Interestingly, their findings suggested that natural resources could help reduce CO2 emissions, contrasting with the widely observed trend of economic growth exacerbating emissions. In the GCC region, Majeed et al. (2021) explored the interplay between natural resource, economic globalization and energy consumption. Their results demonstrated that a fossil fuel energy use and economic growth negatively affected environmental quality. In contrast, renewable energy and resource abundance contributed positively, aligning with UN Sustainable Development Goal 13 (SDG-13).

2.2. Environmental governance and eco-efficiency

Environmental policies have long been recognized as essential tools for addressing environmental pollution, as market forces alone often fail to correct negative externalities caused by polluting activities. Government interventions, therefore, play a critical role in mitigating these externalities (Zheng et al., 2014). One prominent mechanism through which environmental policies influence environmental quality is the *direct cost channel*. This channel operates by altering the financial incentives associated with polluting behaviors. Policies such as carbon taxes or emission permits increase the costs of pollution-intensive activities, encouraging firms to adopt cleaner production practices (Porter and van der Linde, 1995). Stringent environmental policies, characterized by higher pollutant prices or stricter emission limits, make polluting less economically attractive and incentivize reductions in emissions (Yirong, 2022). Conversely, lenient regulations can have the opposite effect, leading to increased pollution.

In addition to the direct cost mechanism, an *indirect channel* has been identified in the literature. This pathway emphasizes the place of environmental policies in stimulating innovation, particularly in clean and green technologies. Stricter environmental regulations increase the opportunity cost of pollution, motivating firms to invest in cleaner technologies. Strategies such as greater public expenditure on renewable energy or supportive tariffs for renewable energy products lower the cost of green innovations, further encouraging their adoption(K. Wang et al., 2020). Moreover, Johnstone et al. (2012) highlighted the importance of government demand for green technologies in driving innovation. Public awareness also plays a significant role, as stricter policies can lead to increased consumer demand for green products (Ahmed, 2020).

Despite these theoretical insights, the empirical evidence regarding the impact of environmental regulations on environmental outcomes is mixed. Many studies have examined the nexus between environmental policy stringency and environmental quality using the OECD Environmental Policy Stringency Index, a composite measure of market- and non-market-based regulations (Hille and Möbius, 2019). On one hand, numerous studies have reported positive environmental impacts of stricter regulations. For instance, Wang et al. (2020) demonstrated that stringent policies improved air quality across 23 OECD countries, while Ahmed (2020) found that environmental policy stringency reduced CO_2 emissions and promoted clean technology innovation in 20 OECD countries. Similarly, Georgatzi et al. (2020) observed that environmental policy stringency reduced transportation-related CO_2 emissions in 12 European countries and spurred environmental patenting activities. In BRICS nations, Wang et al. (2022) found that environmental policy stringency facilitated renewable energy transitions, thereby reducing emissions.

On the other hand, a few studies have identified potential drawbacks to stringent environmental policies. For example, Wolde-Rufael and Mulat-Weldemeskel (2021) reported that EPS initially harmed environmental quality in seven emerging economies, with benefits emerging only after a threshold was reached. Their earlier study (2020) also highlighted the time-dependent nature of policy effectiveness in BRIICTS countries. Furthermore, Yirong (2022) explored the asymmetric effects of environmental policy stringency, finding that both increases and decreases in policy stringency could improve environmental quality in the world's top five emitters, suggesting a complex, nonlinear relationship.

2.3. Theoretical background

This section establishes the economic intuitions linked up with the nexus between eco-efficiency and the respective predictor variables namely: extraordinary economic potential; energy transition; research and development intensity; environmental governance; excess use of natural resources; and the economic importance of international trade. Beginning with the predicted variables, myriad of empirical studies embraces the measurement of ecological footprint, air pollution and water pollution (AWP) to assess the major impacts of humans on the environment (Ahmad and Satrovic, 2024; Danish and Ulucak, 2023; Khan et al., 2023; Musah et al., 2024; Yıldız et al., 2024). Ecological footprint predominantly emphasizes the ecological impact to quantify the consumption rate of natural resources, and the amount of waste created. Similarly, AWP mainly focuses on the quantification of environmental pollution with inadequate attention on the economy-environment nexus. Against this backdrop, the current study establishes on the two proxies for eco-efficiency as economics substantially relates with ecology. Herein, the improvement of ecological quality is deliberated to be a pragmatic path for economies to support the eco-sustainability. Comprehending synchronously the ecological and economic effect uncovers the efficiency of economic sector to utilize natural assets and encourages it to pave way towards sustainable future by concentrating on activities that maintain the biocapacity and impairs ecological footprint to revert to the state of biocapacity reserve. Overall eco-efficiency is quantified as the ratio between the total value-added (PRO) and ecological impact of human activities (ecological footprint); whereas services eco-efficiency is the ratio between services value-added and ecological footprint. The utilization of the alternative proxy for eco-efficiency (SEE) was driven by the fact that overall economic sectors and services could exhibit diverse impacts of the underlying independent variables to offer more substantial insights for policy makers.

Excess use of natural resources has been deemed essential determinant of economic sophistication and ecological sustainability catching the attention of academic community. Available literature scrutinizes the two contrasting views on the EUM-environment nexus. As the first view, natural resources safeguard the supply of raw materials that are deemed vital for global economic potential (Akram et al., 2023). However, resource-intensive countries might experience the faster rise of inputs in comparison with outputs that cause the decreasing returns to scale impeding their sustainability efforts as the available resources will be assigned to reduce the costs rather than to bolster environmental protection (Bhowmik et al., 2024). The EUM accompanied with fluctuating prices, poor environmental governance, and innovation reduction might not only provoke the drop in economic potential but also intensify the ecological pressure (Danish and Ulucak, 2023). Furthermore, EUM extraction boosts air and water pollution, enhances energy intensity, and consequently energy-related ecological problems (Ni et al., 2022). As the second view, natural resources may play a vital role in boosting the ecological sustainability (Ullah et al., 2023a). The favourable ecological effect can be attributed to the fact that a positive correlation between EUM and economic potential empowers countries to allocate the natural resources rents (RESR) towards the achievement of ecological sustainability (Ahmad and Satrovic, 2024). In addition, natural resources rents might facilitate economies to produce and consume eco-friendly goods and services for ecological betterment (Villanthenkodath et al., 2024). Furthermore, EUM can ameliorate ecological sustainability by assigning RESR to sustainable growth beneath the strong environmental governance and research and development intensity (Khan et al., 2023; Shahid et al., 2024).

The strict environmental governance is critical to defend ecological quality and sustainable development (Xie et al., 2023). To achieve these objectives, policy makers are determining and executing policies that will distract procedures harmful to the environment by putting a higher price on such procedures. Herein, good environmental governance has been thoroughly exerted as one of the critical policies to mitigate the ecological pressure towards eco-sustainability (Ullah et al., 2023a). It opts to wipe out the side effects of economic potential i.e. environmental pollution by encouraging eco-innovation. As such, negative externalities of PRO can hardly be restrained only by market forces spotlighting the criticality of government intervention through strict environmental policies. By imposing these policies, governments target to navigate economies towards sustainable growth by abandoning practices that harm the environment (dirty industries) through preservation of natural resources and energy shift towards green sources (Bergougui and Aldawsari, 2024; Borowiec and Papież, 2024). Given the rising environmental concerns, governments should play an active role in curbing ecological pressure, as it is not uncommon that market forces alone fail to assure the proper solution. In virtue of promoting innovation and green energy, good ecological governance is fund effective in boosting the ecological and economic performance of business sector (Zou and Wang, 2024). Conversely, the execution of strict environmental policies might incorporate additional costs which will offset the benefits of technological and efficiency betterments (Danish and Ulucak, 2023). In addition, uncertainty and disorder in national economies may obstruct environmental policies to achieve optimal performance. Xue et al. (2022) further unfolded that ecological sustainability is grounded on the reduction of policy-level disorder by establishing better communication between economic agents. Considering the moderating impact of environmental governance in the relationship between EUM and eco-efficiency, good environmental governance presents a pragmatic tool for the economic activity to enact sustainable practices in resources consumption that will maintain ecological sustainability and advance the efficient consumption of natural resources for the economic and environmental targets (Ali et al., 2022b; Ullah et al., 2023a). Thus, strict environmental policies aim to boost the resource efficiency and productivity to cut down the use of natural resources, hinder the ecological pressure, and increase value-added produced from these resources.

Although international trade is inevitable for the performance of national economies, the unfavourable ecological impacts are wide-ranging. Owing to the substantial rise in anthropogenic emissions associated with international trade, broad range of studies were seeking to investigate the association between the economic importance of international trade (export + import (% GDP), and export/import diversification) and environment. A rise in commercial activity induces a boom in energy consumption which has a potential to reinforce the ecological problems where the diversification of imports (DIM) is not an exception (Ahmad and Jabeen, 2024; Ahmad and Satrovic, 2023; Dai and Du, 2023). The severity of the DIM's ecological impacts hinges on the economies' level of income. As an illustration, a country may specialize in dirty industries in initial stages of economic emancipation to use the advantages of the economies of scale that will not only boost profits and growth but also the energy consumption. As a consequence, initial stages of economic emancipation will amplify the ecological pressure. However, as the level of income increases, countries replace dirty with clean industries to cut down the anthropogenic emissions. Developed countries are also allocating significant resources to prevent ecological harm and obey environmental rules (Cheng et al., 2022; Doğan et al., 2022). Accordingly, developed countries focus on the production that releases fewer anthropogenic emissions and import goods with more pronounced adverse environmental impacts. Thus, Madaleno et al. (2023) unfolded that DIM may encourage the ecological quality of developed countries. Developing countries however can attain less expensive intermediate goods, and if these goods are pollution intensive (i.e. crude oil, steel), the environment of these countries will be impaired (Dai and Du, 2023). International trade may amplify the ecological quality if the government imposes strict environmental policies. Otherwise, the uncertainty of environmental policies may jeopardize the favourable ecological effect of DIM.

The association between extraordinary economic potential and environment has been thoroughly scrutinized in the prior literature. Pursuant to the formulation of environmental Kuznets curve (EKC), Grossman and Krueger (1995) advocated that the developmental stage of growth is coupled with ecological pressure. With the scale effect in place, extraordinary economic potential cuts down the ecological quality. The notion is that in the early period of development, industrialization dominates and escalates the energy use tending to magnify ecological deterioration. EKC paradigm further insinuates that once a target wealth is secured, the technique effect comes on the scene abolishing the harmful ecological impact of extraordinary economic potential. Subsequently, Grossman and Krueger (1995) opt for the concave down (∩) nexus between PRO and ecological pressure. This research builds upon the environmental Kuznets curve (EKC) by incorporating additional explanatory variables such as energy transition, research and development intensity, environmental governance, excess use of natural resources, and twin facet of the economic importance of international trade. In addition, this study opts for the novel indicator of ecological quality namely overall eco-efficiency and services eco-efficiency and scrutinizes the environmental governance-excess use of natural resources moderating impact.

Ecological quality is reliant on PRO since economic development necessitates the consumption of natural resources for the manufacturing process. Herein, in the early period of development, PRO jeopardizes ecological quality but offsets these adverse impacts in the advanced periods of development. Along with PRO, there are other variables that predicted to influence eco-efficiency, such as energy transition and research and development intensity. The transition to clean energy opts for the facilitation of eco-efficiency and maintaining sustainable future. This is since a set of policies embracing energy transition is needed to facilitate green investments and clearance of dirty industries. Clean energy use is endeavouring the shift towards decarbonised economy and flourishes the eco-efficiency against the ecological intensity (Jiang et al., 2022; Ullah et al., 2023b; Yadav et al., 2023). By improving the ecological conditions, energy transition lays the foundation for the reduction of health spending, both private and public. Enabling an inclusive and equitable shift to clean energy provokes prosperous outcomes for eco-efficiency as it relieves environmental pollution and paves way towards climate change mitigation. On the other hand, the energy shift might generate additional costs causing a firm turnover. As a consequence, energy transition might result in an unemployment rate spike (Onwe et al., 2023). Research and development intensity might curtail the pollution attributable to the consumption patterns. With digital transformation in place, research and development intensity arose out as a feasible tool to alleviate ecological pressure and entail a net-zero transition. As an element of innovation, research and development assists in ecosystem management to yield the sustainable use of resources (Akram et al., 2023; Shahid et al., 2024; Ullah et al., 2023b). It can also prompt the changing attitudes to motivate individuals to improve their waste management and diminish energy intensity for ecological sustainability. However, developing countries may witness the harmful environmental impact of research and development intensity as it fosters industry dominated by dirty energy which may hinder the eco-efficiency targets of these countries (Chen et al., 2022; Onwe et al., 2023). If research and development intensity does not foster green tech, the economy is anticipated to face severe ecological consequences.

2.4. *Research gap*

Despite significant progress in examining the dynamics of natural resource use, environmental governance, and eco-efficiency, several critical gaps remain unaddressed in the existing literature.

- First, while prior studies have explored the environmental impacts of excessive natural resource use and eco-efficiency across various regions, few have comprehensively analyzed the moderating role of environmental governance in mitigating these impacts, particularly within the context of OECD countries.
- Second, existing empirical analyses often employ traditional econometric methods that may overlook distributional effects. The application of moment quantile regression, which captures heterogeneity across eco-efficiency quantiles, remains underutilized. This methodological gap limits the understanding of how policy effectiveness varies across different eco-efficiency levels.
- Third, although the link between international trade and environmental sustainability has been examined, the role of trade proxies, such as the import diversification index, in shaping eco-efficiency has received limited empirical attention. Considering trade's dual role in fostering both economic growth and environmental stress, more nuanced approaches are necessary.
- Fourth, current literature primarily focuses on singular eco-efficiency indicators, often overlooking sector-specific impacts. The integration of an alternative eco-efficiency metric, such as services eco-efficiency, could provide deeper insights into sectoral dynamics.
- Finally, while technological innovation and research and development are recognized as key drivers of eco-efficiency, their interaction with environmental governance remains insufficiently explored. How R&D intensity might amplify or mitigate the ecological impact of natural resource use under varying degrees of environmental governance warrants further investigation.

Addressing these gaps could advance the theoretical and empirical understanding of sustainable resource management, offering valuable policy recommendations for fostering eco-efficiency through enhanced environmental governance frameworks.

3. Methodology and data

3.1. Data definition

This study aspires to unriddle the puzzle on whether OECD countries would accomplish the eco-efficiency objectives by virtue of environmental governance scrutinizing the period from 1997 to 2020. The underlying period of time is constructed to assure that each target country is measured every year between 1997 and 2020. For instance, the balanced panel dataset on services value added that provides a proxy for services eco-efficiency is provided from 1997 to 2022, at the same time ecological governance is last accessible in 2020. Table 2 lists the studied OECD members that are at the helm of the excess use of natural resources (Hickel et al., 2022). As a response variable, this study adopts the twin indicators of eco-efficiency to comprehend the ecological and economic impact of the various predictor variables on the overall eco-efficiency and services eco-efficiency. The choice of the second indicator of eco-efficiency was grounded on the notion to ensure the robustness and reliability of our findings. The calculation of the dependent variables is established on total economic value-added (GDP per capita in constant 2015 US$ - PRO) and services value-added (SVL). To achieve the more substantive empirical findings, SVL is averaged on a per-capita basis. After normalizing the SVL variable for the total population (POP), both PRO and SVL per-person gathered from the World Bank (WB, 2023) are divided by ecological footprint per capita sourced from Global Footprint Network (GFN, 2022) to generate the twin features of eco-efficiency (ECEF) where:

$$\begin{cases} TEE = \dfrac{\text{PRO}}{\text{ecological footprint per capita}} \\ EE = \dfrac{\text{Services, value added/total population (POP)}}{\text{ecological footprint per capita}} \end{cases}$$

Table 1 lists the variable and specifies sources and quantification.

Opting for the independent variables, this study scrutinizes the extraordinary economic potential of OECD members depending upon the GDP per capita (constant 2015 US$), its quadratic term, energy transition, excess use of natural resources, and the first proxy for the economic importance of international trade (trade/GDP) accessed from the (WB, 2023). To delve into the impact of research and development intensity on eco-efficiency, this study utilizes the gross domestic spending on research and development (R&D)/GDP sourced from the Organisation for Economic Co-operation and Development database (OECD, 2023). This reliable source is also used to gather the balanced panel dataset on environmental policy stringency index as a proxy for environmental governance (OECD, 2022). Finally, the second proxy for the economic importance of international trade (import diversification index) is collected from the United Nations Conference on Trade and Development (UNCTAD, 2023). Descriptive statistics is further used to assess the features of the underlying variables across OECD members (see Table 2).

Table 1
The details on variables.

Name	Code	Source
Extraordinary economic potential – gross domestic product - GDP per capita (constant 2015 US$)	PRO	WB (2023)
Energy transition – replacement of non-renewables with renewables; the use of renewable energy (share of total)	TRA	WB (2023)
Research and development intensity – gross domestic spending on research and development (R&D)/GDP	RD	OECD (2023)
Environmental governance – environmental policy stringency index	ETG	OECD (2022)
Excess use of natural resources - total natural resources rents (% of GDP)	EUM	WB (2023)
The economic importance of international trade (EIT) 1 – trade (% of GDP)	TRD	WB (2023)
The economic importance of international trade 2 –import diversification index	DI	UNCTAD (2023)
Overall eco-efficiency – PRO/ecological footprint per capita (constant 2015 US$/global hectare)	TEE	GFN (2022); WB (2023); Author calculation
Services eco-efficiency – services, value added (constant 2015 US$ - SVL)/total population (POP)/ ecological footprint per capita (constant 2015 US $/global hectare)	SEE	GFN (2022); WB (2023); Author calculation

As per outcomes in Table 2, the mean overall eco-efficiency amounts to 4905.22 for Canada, 6953.72 for France, 7284.99 for Germany, 6430.48 for Italy, and 6948.16 for Japan, whereas Korea, Spain, United Kingdom, and United States report the following respective values of TEE 4257.71, 5443.57, 8452.53, and 6004.08. Table 3 yields the results for the entire sample manifesting the average TEE value of 6297.83 (2015 US$/global hectare), whereas the average SEE value equals 4191.02 with United States, United Kingdom, Japan, Germany and France revealing the average values above the sample mean. United States ranked first in the extraordinary economic potential, whereas Korea yields the lowest average value. Considering the entire sample average (Table 3), it can be noted that United States, United Kingdom, Germany and Canada are over-performing whereas the other countries are under-performing in terms of PRO. Maximum average research and development intensity in Table 2 is reported for Korea whereas Spain holds on to its bottom position of the RD. Canada is the leader in energy transition and excess use of natural resources whereas France holds to on its top position of the environmental governance. The minimum average value of the environmental governance is unveiled for the United States, whereas the least responsible country for the excess use of natural resources in the sample of selected OECD countries is Japan.

Table 3 further displays the substantial standard deviations in particular for the indicator of eco-efficiency and PRO. The balanced panel dataset divers from the normal distribution scrutinizing that environmental governance and trade (% of GDP) are left-tailed whereas all other variables are right-tailed insinuating a positive skewness coefficient. Also, Table 3 manifests the bivariate correlation between the selected variables. According to the outcomes in Table 3, there is a strong positive linear relationship between TEE and ETG. The statistically significant positive coefficient is also provided between TEE and PRO as well as between TEE and RD. There is a significant negative correlation between TEE and EUM, TEE and DI whereas the other correlation coefficients are not statistically significant. As far as the SEE is scrutinized, Table 3 divulges the statistically significant positive correlation coefficient between SEE and PRO, TRA, ETG, and RD whereas the other coefficients are negative and significant.

3.2. Empirical model

This section establishes the economic intuitions linked up with the nexus between eco-efficiency and the respective predictor variables namely: extraordinary economic potential; energy transition; research and development intensity; environmental governance; excess use of natural resources; and the economic importance of international trade. Beginning with the predicted variables, myriad of empirical studies embrace the measurement of ecological footprint, air pollution and water pollution (AWP) to assess the major impacts of humans on the environment (Ahmad and Satrovic, 2024; Danish and Ulucak, 2023; Khan et al., 2023; Musah et al., 2024; Yıldız et al., 2024). Ecological footprint predominantly emphasizes the ecological impact to quantify the consumption rate of natural resources, and the amount of waste created. Similarly, AWP mainly focuses on the quantification of environmental pollution with inadequate attention on the economy-environment nexus. Against

Table 2
Descriptive statistics concerning individual countries.

Unit of interest	Stat.	TEE	PRO	TRA	ETG	RD	EUM	TRD	DI	SEE
Canada	Mean	4905.22	40,938.75	21.77	2.29	1.82	2.65	68.41	0.22	3228.33
	Stad. dev.	583.28	3019.73	0.59	1.01	0.12	1.43	6.61	0.01	459.60
	Max	6043.72	45,113.10	23.85	3.61	2.02	5.56	82.77	0.23	4130.00
	Min	3995.95	33,861.10	21.13	0.72	1.61	0.33	58.47	0.20	2520.00
	Skewness	0.150	−0.781	1.836	−0.481	0.121	0.448	0.674	−0.200	0.184
	Kurtosis	1.973	2.892	7.595	1.869	1.749	2.132	2.478	3.145	2.032
France	Mean	6953.72	35,391.27	11.44	3.21	2.16	0.05	56.38	0.18	4775.42
	Stad. dev.	895.35	1956.24	2.50	1.10	0.07	0.01	4.82	0.03	705.67
	Max	8654.02	38,832.00	16.87	4.89	2.28	0.07	64.44	0.21	6080.00
	Min	5588.49	30,650.70	8.52	1.47	2.02	0.03	48.03	0.14	3760.00
	Skewness	0.434	−0.639	0.591	−0.329	−0.163	0.234	−0.011	−0.223	0.361
	Kurtosis	2.019	3.215	2.119	1.781	1.957	3.245	1.967	1.401	1.843
Germany	Mean	7284.99	37,886.39	10.06	2.73	2.67	0.12	74.35	0.16	4526.67
	Stad. dev.	1164.76	3437.94	5.00	0.63	0.30	0.06	12.77	0.02	748.76
	Max	9641.30	43,284.60	18.60	3.47	3.17	0.31	88.52	0.19	6140.00
	Min	5582.17	32,313.30	2.82	1.44	2.19	0.05	49.64	0.13	3360.00
	Skewness	0.556	0.050	−0.080	−1.090	0.134	1.238	−0.609	−0.357	0.453
	Kurtosis	2.174	1.652	1.677	2.713	1.770	4.494	1.954	2.385	2.324
Italy	Mean	6430.48	31,816.23	10.99	2.92	1.19	0.10	52.19	0.21	4132.50
	Stad. dev.	704.70	1333.98	5.10	0.96	0.16	0.04	4.93	0.01	603.00
	Max	7729.84	34,081.10	18.69	4.06	1.51	0.17	60.30	0.23	5350.00
	Min	5677.31	29,373.40	4.76	1.33	0.98	0.02	44.59	0.19	3460.00
	Skewness	0.523	−0.050	0.077	−0.349	0.348	0.160	−0.164	−0.185	0.645
	Kurtosis	1.707	1.891	1.360	1.520	1.835	2.456	1.840	1.882	1.972
Japan	Mean	6948.16	33,256.39	5.00	3.20	3.11	0.03	28.08	0.28	4748.33
	Stad. dev.	881.59	1701.97	1.41	0.59	0.18	0.02	6.50	0.02	611.42
	Max	9011.28	36,138.50	8.45	4.06	3.37	0.10	37.43	0.31	6010.00
	Min	5620.28	30,636.30	3.50	1.94	2.72	0.01	18.13	0.26	3730.00
	Skewness	0.546	0.137	1.079	−0.325	−0.641	2.526	−0.220	−0.282	0.201
	Kurtosis	2.630	1.885	3.009	2.253	2.283	8.257	1.564	2.337	2.318
Korea	Mean	4257.71	23,722.12	1.60	2.50	3.21	0.05	76.78	0.34	2357.50
	Stad. dev.	731.12	5516.20	0.98	1.01	0.92	0.03	14.49	0.04	416.26
	Max	5767.00	31,640.20	3.63	3.61	4.80	0.12	105.57	0.43	3250.00
	Min	2942.94	14,195.80	0.68	0.75	2.02	0.03	57.52	0.27	1610.00
	Skewness	0.128	−0.180	0.786	−0.859	0.235	1.089	0.605	0.307	0.210
	Kurtosis	2.110	1.807	2.053	2.048	1.616	2.971	2.316	2.893	2.198
Spain	Mean	5443.57	25,354.08	12.25	2.13	1.15	0.05	58.29	0.21	3525.42
	Stad. dev.	989.15	1719.10	4.10	0.56	0.19	0.01	5.42	0.03	831.10
	Max	6969.70	28,087.90	19.35	2.83	1.41	0.07	67.57	0.26	4750.00
	Min	4233.13	21,117.00	7.30	1.11	0.78	0.04	46.99	0.16	2550.00
	Skewness	0.163	−0.691	0.193	−0.747	−0.565	0.349	0.055	0.186	0.143
	Kurtosis	1.335	3.263	1.376	2.085	2.001	2.019	2.266	2.087	1.300
United Kingdom	Mean	8452.53	42,484.33	4.17	2.55	1.86	0.70	56.23	0.22	5832.92
	Stad. dev.	1869.33	3050.23	3.81	0.97	0.44	0.29	4.99	0.03	1481.89
	Max	12,271.73	47,491.60	13.50	3.86	2.93	1.34	64.13	0.30	8870.00
	Min	6531.36	35,776.40	0.85	1.00	1.53	0.17	49.31	0.18	4160.00
	Skewness	0.807	−0.470	1.023	−0.356	1.228	−0.040	0.168	0.800	0.703
	Kurtosis	2.251	2.744	2.855	1.751	3.000	2.594	1.659	3.875	2.149
United States	Mean	6004.08	53,092.05	7.34	1.95	2.72	0.85	26.30	0.20	4592.08
	Stad. dev.	1146.47	4334.34	2.11	0.71	0.24	0.40	2.78	0.01	913.65
	Max	8279.26	60,698.00	11.16	3.03	3.47	1.93	30.84	0.22	6440.00
	Min	4299.23	44,267.90	4.51	1.08	2.48	0.23	22.29	0.17	3270.00
	Skewness	0.259	−0.210	0.200	0.202	1.603	0.741	0.134	−0.212	0.211
	Kurtosis	1.887	2.363	1.663	1.545	5.597	3.578	1.749	1.957	1.868

this backdrop, the current study establishes on the two proxies for eco-efficiency as economics substantially relates with ecology. Herein, the improvement of ecological quality is deliberated to be a pragmatic path for economies to support the eco-sustainability. Comprehending synchronously the ecological and economic effect uncovers the efficiency of economic sector to utilize natural assets and encourages it to pave way towards sustainable future by concentrating on activities that maintain the biocapacity and impairs ecological footprint to revert to the state of biocapacity reserve. Overall eco-efficiency is quantified as the ratio between the total value-added (PRO) and ecological impact of human activities (ecological footprint); whereas services eco-efficiency is the ratio between services value-added and ecological footprint. The utilization of the alternative proxy for eco-efficiency (SEE) was driven by the fact that overall economic sectors and services could exhibit diverse impacts of the underlying independent variables to offer more substantial insights for policy makers.

Excess use of natural resources has been deemed essential determinant of economic sophistication and ecological sustainability catching the attention of academic community. Available literature scrutinizes the two contrasting views on the EUM-environment nexus. As the first view, natural resources safeguard the supply of raw materials that are deemed vital for global economic potential (Akram et al., 2023). However, resource-intensive countries might experience the faster rise of inputs in comparison with outputs that cause the decreasing returns to scale impeding their sustainability efforts as the available resources will be assigned to reduce the costs rather than to bolster environmental protection (Bhowmik et al., 2024). The EUM accompanied with fluctuating prices, poor environmental governance, and innovation reduction might not only provoke the drop in economic potential but also intensify the ecological pressure (Danish and Ulucak, 2023). Furthermore, EUM extraction boosts air and water pollution, enhances energy intensity, and consequently energy-related ecological problems (Ni et al., 2022).

Table 3
Descriptive statistics concerning the overall sample and bivariate correlation.

Stat./Var.	TEE	PRO	TRA	ETG	RD	EUM	TRD	DI	SEE
Mean	6297.83	35,993.51	9.40	2.61	2.21	0.51	55.22	0.22	4191.02
Stad. dev.	1605.07	9081.00	6.45	0.95	0.82	0.95	18.73	0.06	1250.68
Max	12,271.73	60,698.00	23.85	4.89	4.80	5.56	105.57	0.43	8870.00
Min	2942.94	14,195.80	0.68	0.72	0.78	0.01	18.13	0.13	1610.00
Skewness	0.744	0.336	0.566	−0.235	0.449	3.031	−0.074	1.064	0.621
Kurtosis	4.287	3.140	2.263	2.259	2.947	12.861	2.748	3.995	4.150
TEE	1								
PRO	0.423a 0.000	1							
TRA	0.108 0.114	0.195a 0.004	1						
ETG	0.579a 0.000	0.083 0.222	0.225a 0.001	1					
RD	0.141b 0.038	0.209a 0.002	−0.307a 0.000	0.285a 0.000	1				
EUM	−0.244a 0.000	0.374a 0.000	0.475a 0.000	−0.241a 0.000	−0.121c 0.077	1			
TRD	−0.057 0.401	−0.322a 0.000	0.289a 0.000	0.151b 0.026	−0.007 0.915	0.114c 0.094	1		
DI	−0.247a 0.000	−0.427a 0.000	−0.341a 0.000	0.112c 0.099	0.360a 0.000	−0.108 0.113	0.036 0.597	1	
SEE	0.971a 0.000	0.546a 0.000	0.126c 0.065	0.529a 0.000	0.129c 0.058	−0.172b 0.011	−0.217a 0.001	−0.260a 0.000	1

Note: p values underlined, a – $p < 1$ %; b – $p < 5$ %; c – $p < 10$ %.

As the second view, natural resources may play a vital role in boosting the ecological sustainability (Ullah et al., 2023a). The favourable ecological effect can be attributed to the fact that a positive correlation between EUM and economic potential empowers countries to allocate the natural resources rents (RESR) towards the achievement of ecological sustainability (Ahmad and Satrovic, 2024). In addition, natural resources rents might facilitate economies to produce and consume eco-friendly goods and services for ecological betterment (Villanthenkodath et al., 2024). Furthermore, EUM can ameliorate ecological sustainability by assigning RESR to sustainable growth beneath the strong environmental governance and research and development intensity (Khan et al., 2023; Shahid et al., 2024).

The strict environmental governance is critical to defend ecological quality and sustainable development (Xie et al., 2023). To achieve these objectives, policy makers are determining and executing policies that will distract procedures harmful to the environment by putting a higher price on such procedures. Herein, good environmental governance has been thoroughly exerted as one of the critical policies to mitigate the ecological pressure towards eco-sustainability (Ullah et al., 2023a). It opts to wipe out the side effects of economic potential i.e. environmental pollution by encouraging eco-innovation. As such, negative externalities of PRO can hardly be restrained only by market forces spotlighting the criticality of government intervention through strict environmental policies. By imposing these policies, governments target to navigate economies towards sustainable growth by abandoning practices that harm the environment (dirty industries) through preservation of natural resources and energy shift towards green sources (Bergougui and Aldawsari, 2024; Bergougui and Meziane, 2025; Borowiec and Papież, 2024). Given the rising environmental concerns, governments should play an active role in curbing ecological pressure, as it is not uncommon that market forces alone fail to assure the proper solution. In virtue of promoting innovation and green energy, good ecological governance is fund effective in boosting the ecological and economic performance of business sector (Zou and Wang, 2024). Conversely, the execution of strict environmental policies might incorporate additional costs which will offset the benefits of technological and efficiency betterments (Danish and Ulucak, 2023). In addition, uncertainty and disorder in national economies may obstruct environmental policies to achieve optimal performance. Xue et al. (2022) further unfolded that ecological sustainability is grounded on the reduction of policy-level disorder by establishing better communication between economic agents. Considering the moderating impact of environmental governance in the relationship between EUM and eco-efficiency, good environmental governance presents a pragmatic tool for the economic activity to enact sustainable practices in resources consumption that will maintain ecological sustainability and advance the efficient consumption of natural resources for the economic and environmental targets (Ali et al., 2022a; Ullah et al., 2023a). Thus, strict environmental policies aim to boost the resource efficiency and productivity to cut down the use of natural resources, hinder the ecological pressure, and increase value-added produced from these resources.

Although international trade is inevitable for the performance of national economies, the unfavourable ecological impacts are wide-ranging. Owing to the substantial rise in anthropogenic emissions associated with international trade, broad range of studies were seeking to investigate the association between the economic importance of international trade (export + import (% GDP), and export/import diversification) and environment. A rise in commercial activity induces a boom in energy consumption which has a potential to reinforce the ecological problems where the diversification of imports (DIM) is not an exception (Ahmad and Jabeen, 2024; Ahmad and Satrovic, 2023; Dai and Du, 2023). The severity of the DIM's ecological impacts hinges on the economies' level of income. As an illustration, a country may specialize in dirty industries in initial stages of economic emancipation to use the advantages of the economies of scale that will not only boost profits and growth but also the energy consumption. As a consequence, initial stages of economic emancipation will amplify the ecological pressure. However, as the level of income increases, countries replace dirty with clean industries to cut down the anthropogenic emissions. Developed countries are also allocating significant resources to prevent ecological harm and obey environmental rules (Cheng et al., 2022; Doğan et al., 2022). Accordingly, developed countries focus on the production that releases fewer anthropogenic emissions and import goods with more pronounced adverse environmental impacts. Thus, Madaleno et al. (2023) unfolded that DIM may encourage the ecological quality of developed countries. Developing countries however can attain less expensive intermediate goods, and if these goods are pollution intensive (i.e. crude oil, steel), the environment of these countries will be impaired (Dai and Du, 2023). International trade may amplify the ecological quality if the government imposes strict environmental policies. Otherwise, the uncertainty of environmental policies may jeopardize the favourable ecological effect of DIM.

The association between extraordinary economic potential and environment has been thoroughly scrutinized in the prior literature. Pursuant to the formulation of environmental Kuznets curve (EKC), Grossman and Krueger (1995) advocated that the developmental stage of growth is coupled with ecological pressure. With the scale effect in place, extraordinary economic potential cuts down the ecological quality. The notion is that in the early period of development, industrialization dominates and escalates the energy use tending to magnify ecological deterioration. EKC paradigm further insinuates that once a target wealth is secured, the technique effect comes on the scene abolishing the harmful ecological impact of extraordinary economic potential. Subsequently, Grossman and Krueger (1995) opt for the concave down (∩) nexus between PRO and ecological pressure. This research builds upon the environmental Kuznets curve (EKC) by incorporating additional explanatory variables such as energy transition, research and development intensity, environmental governance, excess use of natural resources, and twin facet of the economic importance of international trade. In addition, this study opts for the novel indicator of ecological quality namely overall eco-efficiency and services eco-efficiency and scrutinizes the environmental governance-excess use of natural resources moderating impact.

Ecological quality is reliant on PRO since economic development necessitates the consumption of natural resources for the manufacturing process. Herein, in the early period of development, PRO jeopardizes ecological quality but offsets these adverse impacts in the advanced periods of development. Along with PRO, there are other variables that predicted to influence eco-efficiency, such as energy transition and research and development intensity. The transition to clean energy opts for the facilitation of eco-efficiency and maintaining sustainable future. This is since a set of policies embracing energy transition is needed to facilitate green investments and clearance of dirty industries. Clean energy use is endeavouring the shift towards decarbonised economy and flourishes the eco-efficiency against the ecological intensity (Jiang et al., 2022; Ullah et al., 2023b; Yadav et al., 2023). By improving the ecological conditions, energy transition lays the foundation for the reduction of health spending, both private and public. Enabling an inclusive and equitable shift to clean energy provokes prosperous outcomes for eco-efficiency as it relieves environmental pollution and paves way towards climate change mitigation. On the other hand, the energy shift might generate additional costs causing a firm turnover. As a consequence, energy transition might result in an unemployment rate spike (Onwe et al., 2023). Research and development intensity might curtail the pollution attributable to the consumption patterns. With digital transformation in place, research and development intensity arose out as a feasible tool to alleviate ecological pressure and entail a net-zero transition. As an element of innovation, research and development assists in ecosystem management to yield the sustainable use of resources (Akram et al., 2023; Shahid et al., 2024; Ullah et al., 2023b). It can also prompt the changing attitudes to motivate individuals to improve their waste management and diminish energy intensity for ecological sustainability. However, developing countries may witness the harmful environmental impact of research and development intensity as it fosters industry dominated by dirty energy which may hinder the eco-efficiency targets of these countries (Chen et al., 2022; Onwe et al., 2023). If research and development intensity does not foster green tech, the economy is anticipated to face severe ecological consequences.

Through the lens of the underlying associations among the studied variables proposed in the preceding paragraphs, this research evaluates the relationships between eco-efficiency and its determinants building upon the EKC theoretical framework. Our model follows the studies of (Ahmad and Jabeen, 2024; Arjun and Mishra, 2024; Shi et al., 2024) and is expressed by the following estimation equation as (Eq. (1)):

$$ECEF_{it} = f\left(PRO_{it}, PRO2_{it}, TRA_{it}, ETG_{it}, RD_{it}, EUM_{it}, EIT_{it}\right) \tag{1}$$

To make sure that our dataset is uniform, the natural logarithms of all variables in Table 1 are adopted in this study as outlined by (Bhowmik et al., 2024; Satrovic et al., 2024a). After the transformation, the log-linear estimation equation of the eco-efficiency is formulated below (Eq. (2)):

$$\begin{aligned} LECEF_{it} = {} & \omega_0 + \omega_1 LPRO_{it} + \omega_2 LPRO2_{it} + \omega_3 LTRA_{it} + \omega_4 LETG_{it} \\ & + \omega_5 LRD_{it} + \omega_6 LEUM_{it} + \omega_7 \mathrm{LEIT}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \end{aligned} \tag{2}$$

The coefficients $\omega_1 - \omega_7$ signal eco-efficiency assessments for the underlying independent variables scrutinizing nine OECD members (i) during the period (t) from 1997 to 2020. An intercept is shown by ω_0, whereas the residual term is indicated by $\varepsilon_{\mathrm{it}}$. The present study adopts the two indicators of eco-efficiency (ECEF) namely overall eco-efficiency (TEE) and services eco-efficiency (SEE). Term L connotes the natural log form of the variables. $PRO, PRO2, TRA, ETG, RD, EUM$, and EIT delineate regressors namely: extraordinary economic potential, extraordinary economic potential squared, energy transition, environmental governance, research and development intensity, excess use of natural resources and the economic importance of international trade. Trade (% of GDP) - TRD and import diversification index - DI are accustomed to measure the economic importance of international trade.

Emanating for the left-hand side of the Eq. (2), prior studies employ dozens of dependent variables such as greenhouse gasses emissions and ecological footprint to proxy the environment. However, these indicators are unsuccessful in opting for the economic aspect of eco- and environmental sustainability indicators. To fill the void, this study hinges upon the two proxies for eco-efficiency namely overall and services eco-efficiency (Ahmad and Jabeen, 2024; Apostu et al., 2023; Sun and Gao, 2023b). As of the right-hand side of Eq. (2), myriads of studies postulate the feasible direction on the eco-efficiency and its determinants. In the first place, the concave down relationship between PRO and environmental/ecological indicators is firmly established in previous empirical works (Borowiec and Papież, 2024; Madaleno et al., 2023; Satrovic et al., 2024a; Xie et al., 2023). If certified, EKC phenomenon insinuates that PRO reduces eco-efficiency in the early stages of growth but furnishes the upswing in ecological quality at the later stages (i.e. $\frac{\partial \mathrm{ECEF}_{\mathrm{it}}}{\partial \mathrm{PRO}_{\mathrm{it}}} < 0$ and $\frac{\partial \mathrm{ECEF}_{\mathrm{it}}}{\partial \mathrm{PRO2}_{\mathrm{it}}} > 0$). Excess use of natural resources is considered a prominent feature to alleviate or ameliorate eco-efficiency (i.e. $\frac{\partial ECEF_{it}}{\partial EUM_{it}} < 0$ and $\frac{\partial ECEF_{it}}{\partial EUM_{it}} > 0$). As for example, resource-intensive countries may encounter the decreasing returns to scale provoking the alleviation of ecological patterns (Satrovic et al., 2024b). Similarly, price variability, stagnation in innovation, and weak environmental management may initiate eco-unfriendly practices. By way of illustration (Danish and Ulucak, 2023; Ni et al., 2022) signal that weak environmental management reinforces pollution associated with the extraction of natural resources and the intensification of fossil fuels. As opposed to that, natural resources rents (RESR) may be a prominent facet to ameliorate eco-efficiency as economically empowered countries may direct more funds in helping protect eco-systems (Bhowmik et al., 2024; Ullah et al., 2023a). In addition, RESR may encourage governments to direct investments in green innovation to bring eco-efficiency targets closer into view (Khan et al., 2023; Shahid et al., 2024). Strengthening environmental governance may establish an advantageous impact on eco-efficiency (i.e. $\frac{\partial \mathrm{ECEF}_{\mathrm{it}}}{\partial \mathrm{ETG}_{\mathrm{it}}} > 0$) as projected by (Borowiec and Papież, 2024; Ullah et al., 2023a; Xie et al., 2023; Zou and Wang, 2024). On the other hand, economic fluctuations may prevent the efficiency of environmental policies in reaching eco-efficiency targets (i.e. $\frac{\partial \mathrm{ECEF}_{\mathrm{it}}}{\partial ETG_{\mathrm{it}}} < 0$) opting for the previous findings of (Danish and Ulucak, 2023; Xue et al., 2022). International trade can lead to economic sophistication and better standard of living, but there are also the environmental impacts of expanded trade that need to be firmly considered. As suggested by (Ahmad and Jabeen, 2024; Cheng et al., 2022; Dai and Du, 2023) international trade might be one of the substantial determinants of ecological pressure (i.e. $\frac{\partial \mathrm{ECEF}_{\mathrm{it}}}{\partial EIT_{\mathrm{it}}} < 0$). This is attributed to the upswing in energy consumption associated with commercial activity. On the flip side, international trade is anticipated to facilitate ecological quality (i.e. $\frac{\partial \mathrm{ECEF_{it}}}{\partial EIT_{\mathrm{it}}} > 0$) as (Ahmad and Satrovic, 2023; Doğan et al., 2022; Madaleno et al., 2023) outlined the ecological benefiting impact of EIT. This is since developed countries export pollution by outsourcing their carbon intensity activities, and importing eco-unfriendly commodities. In addition, international trade may encourage the circulation of green tech and more efficient production methods propelling energy efficiency and efficient use of natural resources. According to the Jiang et al., 2022; Ullah et al., 2023b; Yadav et al., 2023) energy transition is projected to facilitate eco-efficiency (i.e. $\frac{\partial ECEF_{it}}{\partial TRA_{it}} > 0$), while Onwe et al. (2023) established on the harmful effect of energy transition on eco-efficiency such that (i.e. $\frac{\partial ECEF_{it}}{\partial TRA_{it}} < 0$). As far as research and development intensity is considered, (Akram et al., 2023; Shahid et al., 2024; Ullah et al., 2023b) support the view of favourable ecological impacts of RD (i.e. $\frac{\partial \mathrm{ECEF_{it}}}{\partial \mathrm{RD_{it}}} > 0$). However, (Chen et al., 2022; Onwe et al., 2023) elaborated that research and development intensity might ameliorate ecological pressure (i.e. $\frac{\partial \mathrm{ECEF_{it}}}{\partial \mathrm{RD_{it}}} < 0$).

Eq. (2) further looks into the interaction term of environmental governance and natural resources to scrutinize the indirect impact of EUM on overall and services eco-efficiency via the environmental governance channel as proposed by Bhowmik et al. (2024). The model is specified as (Eq. (3)):

$$\begin{aligned} LECEF_{it} &= \omega_0 + \omega_1 LPRO_{it} + \omega_2 LPRO2_{it} + \omega_3 LTRA_{it} + \omega_4 LMod_{it} \\ &\quad + \omega_5 LRD_{it} + \omega_6 LEUM_{it} + \omega_7 \mathrm{LEIT_{it}} + \varepsilon_{\mathrm{it}} \end{aligned} \tag{3}$$

The interaction term is symbolized as $Mod = ETG^*EUM$. Strengthening environmental governance may act in place of improving the natural resources allocation, conservation of natural assests, and boosting the eco-friendly extracting practices. Herein, (Ali et al., 2022a; Ullah et al., 2023a) elucidated the advantageous ecological impact of a moderator (i.e. $\frac{\partial ECEF_{\mathrm{it}}}{\partial (ETG_{\mathrm{it}}{}^*\mathrm{EUM_{it}})} > 0$).

3.3. Methodology

Longitudinal data may face severe issues yielding inconsistent findings if neglected. To safeguard the unbiased estimates, the methodology framework begins with detecting the cross-sectional dependence (ISCR) and slope heterogeneity (ISH). Accordingly, to inspect whether our dataset is independent across the investigative laboratory of nine OECD members, this study applies the Pesaran (2004) ISCR test which calculates on the following equation (Eq. (4)):

$$\mathrm{ISCR} = \sqrt{\frac{2\mathrm{T}}{\mathrm{N(N-1)}}}\left(\sum_{\mathrm{i=1}}^{\mathrm{N-1}}\sum_{\mathrm{j=i+1}}^{\mathrm{N}}\widehat{\rho}_{\mathrm{ij}}\right) \tag{4}$$

In Eq. (4), the period under examination is denoted by T, whereas the counties of interest are signalied by N. $\widehat{\rho}_{ij}$ is the notion for bivariate correlation which is shown below (Eq. (5)):

$$\widehat{\rho}_{ij} = \widehat{\rho}_{ji} = \frac{\sum_{t=1}^{T}\varepsilon_{it}\varepsilon_{jt}}{\left(\sum_{t=1}^{T}\varepsilon_{it}^2\right)^{\frac{1}{2}}\left(\sum_{t=1}^{T}\varepsilon_{jt}^2\right)^{\frac{1}{2}}} \tag{5}$$

The null hypothesis supposes that our balanced panel data are not dependent across inspected countries, whereas the H1 is in conformity with the dependence of longitudinal data. Furthermore, this study looks over the premise of slope homogeneity. Pursuing upon it, we establish on the ISH test commenced by Pesaran (2007). Equations below provide a mathematical expression of the test (Eq. (6) and Eq. (7)):

$$\widehat{\Delta}_{ISH} = \sqrt{N} \bullet \sqrt{2k} \bullet \left(N^{-1} \bullet \widehat{S} - k\right) \tag{6}$$

$$\widehat{\widehat{\Delta}}_{ISH} = \sqrt{\mathrm{N}} \bullet \left(\frac{2\mathrm{k} \bullet (\mathrm{T-k-1})}{\mathrm{T+1}}\right)^{-1/2} \bullet \left(\mathrm{N}^{-1} \bullet \widehat{\mathrm{S}} - 2\mathrm{k}\right) \tag{7}$$

Based on the (Eq. (6) and Eq. (7)), $\widehat{\Delta}_{\mathrm{ISH}}$ refers to the ISH and adjusted ISH Pesaran (2007) test. The H0 endorses the homogeneous slopes, whereas H1 posits that the underlying model encounters the heterogeneous slopes. Under the assumptions of ISCR and ISH, there is a need to develop appropriate analytical approaches to cope with these issues. In this vein, our study proposes the second generation stationarity test (STE) by Pesaran (2007) as the reliance on the conventional tests may yield the incorrect results. Cross-sectional Augmented Dickey-Fuller (CADF) sets out as (Eq. (8)):

$$\Delta Y_{it} = \rho_i + \rho_i Y_{it-1} + \rho_i X_{t-1} + \rho_i T + \sum_{j=1}^{n}\rho_{ij}\Delta Y_{it-j} + \theta_{it} \tag{8}$$

Where Y_{it} represents underlying panel dataset, the first difference of the variables is signified by Δ, while θ_{it} expresses the residual. STE test established on CADF averages and can be econometrically articulated as (Eq. (9)):

$$STE = N^{-1}\sum_{i=1}^{n} CADF \tag{9}$$

Next, this study utilizes the Westerlund (2005) cointegration test to look into the long-run association between studied variables. Under the H0, this test supposes no cointegration, whereas alternative hypothesis presumes that eco-efficiency has a long-term nexus with the regressors. The second-generation cointegration (CTGT) test performs well if there is the dependence of longitudinal data.

Once ISCR and ISH issues are confirmed as well as the long-term association between the variables, our study establishes on Machado and Silva (2019) estimation technique namely MACS. The choice of this method was wheeled by the fact that conventional analytical techniques provide average effects only and can potentially obtain overrated or underestimated predictions. In addition, these tests do not yield consistent findings in the case of ISCR. Another advantage of MACS over traditional estimators is that it provides trustworthy findings under the endogeneity problem and works well if the distribution deviates from normal. It is eminent in addressing the nonlinearity problem and enables the assessment of location-related asymmetry. This method is also effective if the estimated model establishes on the heterogenous slopes. Further advantage of MACS stems from its ability to estimate regression coefficients at diverse conditional quantiles of overall and service eco-efficiency. Given the variety of eco-efficiency indicators, MACS is capable to provide country-wise breakdown that might provide vital directions for the decisions makers. Contrary to traditional techniques, MACS renders consistent findings in the case of non-normal distribution of longitudinal data. Given these characteristics, MACS is proved to be robust analytical framework as highly recommended by (Ullah et al., 2023b; Shi et al., 2024; Bergougui et al., 2025). The MACS can be formulated as (Eq. (10)):

$$Q_{Y_{it}}(\tau|X_{it}) = \alpha(\tau)'X_{it} + \beta_i, i = 1, \ldots, N, t = 1, \ldots, T \tag{10}$$

In Eq. (10), Y_{it} is the representation of overall and services eco-efficiency (twin features of eco-efficiency); X_{it} stands for the regressors, namely $LPRO, LPRO2, LTRA, LETG, LRD, LEUM$, and $LEIT$. Unknown parameters are symbolized by $\alpha(\tau)$ while individual effects are denoted by β_i. Eq. (10) is supplemented with variables shown in Table 1 to outline the augmented version of EKC theoretical framework following the studies of (Ahmad and Jabeen, 2024; Arjun and Mishra, 2024; Shi et al., 2024). The formulation of the underlying models as below (Model 1 – Eq. (11); Model 2 – Eq. (12); Model 3 – Eq. (13); Models 4 – Eq. (14)):

$$Q_{LTEE}(\tau|X_{it}) = a_{1\tau}LPRO_{it} + a_{2\tau}LPRO2_{it} + a_{3\tau}LTRA_{it} + a_{4\tau}LETG_{it} + a_{5\tau}LRD_{it} + a_{6\tau}LEUM_{it} + a_{7\tau}LTRD_{it} + \beta_i \tag{11}$$

$$Q_{LSEE}(\tau|X_{it}) = a_{1\tau}LPRO_{it} + a_{2\tau}LPRO2_{it} + a_{3\tau}LTRA_{it} + a_{4\tau}LETG_{it} + a_{5\tau}LRD_{it} + a_{6\tau}LEUM_{it} + a_{7\tau}LTRD_{it} + \beta_i \tag{12}$$

$$Q_{LTEE}(\tau|X_{it}) = a_{1\tau}LPRO_{it} + a_{2\tau}LPRO2_{it} + a_{3\tau}LTRA_{it} + a_{4\tau}LMod_{it} + a_{5\tau}LRD_{it} + a_{6\tau}LEUM_{it} + a_{7\tau}LTRD_{it} + \beta_i \tag{13}$$

$$Q_{LSEE}(\tau|X_{it}) = a_{1\tau}LPRO_{it} + a_{2\tau}LPRO2_{it} + a_{3\tau}LTRA_{it} + a_{4\tau}LMod_{it} + a_{5\tau}LRD_{it} + a_{6\tau}LEUM_{it} + a_{7\tau}LTRD_{it} + \beta_i \tag{14}$$

In Eqs. (11–14), Mod = ETG*EUM.

Robustness check is performed by applying the Driscoll-Kraay estimator (ESDK) that empirically estimates the formulated models. This is a trustworthy estimator if the sample is challenged by ISCR, autocorrelation, and heteroscedasticity issue. In addition, ESDK is a nonparametric analytical framework flexible enough to utilize balanced or unbalanced longitudinal data. It is capable of estimating comprehensive time dimensions and as such intensively used in studies to date (Arjun and Mishra, 2024; Satrovic et al., 2024b). Besides, the soundness of our findings further establishes on the alternative indicator of EIT. Models supplemented with the import diversification index (DI) follow the augmented EKC paradigm (Ahmad and Jabeen, 2024; Arjun and Mishra, 2024; Shi et al., 2024) and are manifested as (Model 5 – Eq. (15); Model 6 – Eq. (16); Model 7 – Eq. (17); Models 8 – Eq. (18)):

$$Q_{LTEE}(\tau|X_{it}) = a_{1\tau}LPRO_{it} + a_{2\tau}LPRO2_{it} + a_{3\tau}LTRA_{it} + a_{4\tau}LETG_{it} + a_{5\tau}LRD_{it} + a_{6\tau}LEUM_{it} + a_{7\tau}LDI_{it} + \beta_i \tag{15}$$

$$Q_{LSEE}(\tau|X_{it}) = a_{1\tau}LPRO_{it} + a_{2\tau}LPRO2_{it} + a_{3\tau}LTRA_{it} + a_{4\tau}LETG_{it} + a_{5\tau}LRD_{it} + a_{6\tau}LEUM_{it} + a_{7\tau}LDI_{it} + \beta_i \tag{16}$$

$$Q_{LTEE}(\tau|X_{it}) = a_{1\tau}LPRO_{it} + a_{2\tau}LPRO2_{it} + a_{3\tau}LTRA_{it} + a_{4\tau}LMod_{it} + a_{5\tau}LRD_{it} + a_{6\tau}LEUM_{it} + a_{7\tau}LDI_{it} + \beta_i \tag{17}$$

$$Q_{LSEE}(\tau|X_{it}) = a_{1\tau}LPRO_{it} + a_{2\tau}LPRO2_{it} + a_{3\tau}LTRA_{it} + a_{4\tau}LMod_{it} + a_{5\tau}LRD_{it} + a_{6\tau}LEUM_{it} + a_{7\tau}LDI_{it} + \beta_i \tag{18}$$

The next section furnishes empirical outcomes and showcases economic interpretations.

4. Empirical results

4.1. Feedback from pre-estimation analysis

It was essential to gauge the properties of the underlying variables ahead of identifying the elasticity coefficients. In this respect, the underlying study considers the two most prevalent issues

accompanying longitudinal data, namely cross-sectional dependence (ISCR) and slope heterogeneity (ISH). Table 4 furnishes the findings of Pesaran (2004) ISCR test and Pesaran (2007) ISH test.

The findings of the ISH test in Table 4 portray the significant test statistics ($p < 0.01$) to deny the null hypothesis theorizing the homogeneous slope in support of the H1 postulating the heterogeneous slope. Both delta and adjusted delta statistics lead us to conclude that underlying models' slopes manifest heterogeneity. The justification of these outcomes can be due to the variations in economic structures of the target OECD members. On the other hand, Table 4 furnishes the outcomes of Pesaran' (2004) test endorsing the occurrence of ISCR. The observed model specifications in Table 4 disapprove the H0 on independent series across sections backing the H1 at the 1 % significance levels. It discloses that vigorous shifts in overall and services eco-efficiency, extraordinary economic potential, energy transition, research and development intensity, environmental governance, excess use of natural resources, and the economic importance of international trade in an OECD member are anticipated to alter other members (Satrovic et al., 2024c). Given these findings it can be asserted that in the time span between 1997 and 2020, OECD members undergo steadily growing economic and financial interrelatedness. The unattended ISCR and ISH concerns of longitudinal data may hinder the quality of dataset and furnish unsound results. Against this setting, this study uses the methods allowed to cope with these issues going ahead with the second-generation stationary test (STE) summarized in Table 5.

Table 4
Slope heterogeneity and cross-sectional dependence - outcomes.

Stat./Model	Model 1	Model 2	Model 5	Model 6
Δ	7.628a	7.625a	7.489a	7.410a
	0.000	0.000	0.000	0.000
Δ adj.	9.649a	9.645a	9.473a	9.373a
	0.000	0.000	0.000	0.000
ISCR	5.856a	4.694a	4.346a	3.556a
	0.000	0.000	0.000	0.000

Note: p values underlined, a – p < 1 %; b – p < 5 %; c – p < 10 %; Δ captures delta, and Mod = ETG*EUM.

As seen in Table 5, STE test scores are not reported significant for natural logarithms of extraordinary economic potential, extraordinary economic potential squared, eco-efficiency, energy transition, research and development intensity, environmental governance, excess use of natural resources, and the economic importance of international trade approving the assumption of non-stationarity at levels. For the first difference form, the p values below 1 % guide us towards the refusal of null hypothesis giving support to H1 that assumes stationarity of the inspected panel dataset. After affirming that the first differences are all integrated of order one (i.e. I(1)), we apply the cointegration test as portrayed in Table 6.

The Westerlund's (2005) CTGT test assesses whether the proxies for eco-efficiency converge to the long-term equilibrium. As seen in Table 6, the null-hypothesis of no cointegration cannot be accepted given the statistically significant values of test statistics ($p < 0.01$). This offers the evidence that OECD members' economy is apt to secure soundness in the long-term after any vigorous shifts in the factors of eco-efficiency. Herein, the outcomes of Westerlund's (2005) CTGT test manifest the cointegration linkage amid the studied variables.

4.2. Estimated outcomes and discussion

Given the cointegration association between our variables, this study further assesses the regression coefficients. The outcomes of ESDK and MACS estimators are thereby furnished in Table 7 (quantiles 0.1, 0.3, 0.5, 0.7 and 0.9) and Fig. 2 (the remaining quantiles).

4.2.1. Extraordinary economic potential and eco-efficiency

As presented in Table 7 and Fig. 2, this study evaluates two types of

Table 5
Unit root approach.

Variable	URT (intercept & trend)	
	Level	First difference
LPRO	−2.533	−3.762a
LPRO2	−2.519	−3.708a
LTRA	−2.213	−5.138a
LETG	−3.366	−5.349a
LRD	−1.957	−3.430a
LEUM	−2.546	−5.918a
LTRD	−1.255	−3.363a
LDI	−2.788	−4.895a
LTEE	−3.140	−5.382a
LSEE	−3.277	−5.605a
LMod	−3.029	−5.959a

Note: p values underlined, a – p < 1 %; b – p < 5 %; c – p < 10 %.

Table 6
Feedback on cointegration.

Test/Model	Model 1	Model 2	Model 5	Model 6
Westerlund's (2005)	6.038a	4.913a	6.908a	6.069a
	0.000	0.000	0.000	0.000

Note: p values underlined, a – $p < 1$ %; b – $p < 5$ %; c – $p < 10$ %.

models—overall eco-efficiency (O-form models) and services eco-efficiency (S-form models)—as dependent variables. Both models are analyzed with and without incorporating the joint effects of ETG and EUM. Table 7 illustrates that the two O-form models highlight a negative relationship between extraordinary economic potential and overall eco-efficiency. Simultaneously, a statistically significant positive association between LPRO2 and the dependent variable is evident.

An O-form model without moderation reveals a decreasing trend in the coefficients of LPRO, which are significant across OECD members with low, medium, and high eco-efficiency. In contrast, the coefficients of LPRO2 are significantly positive at varying quantiles of overall eco-efficiency, demonstrating an increasing trend. Similarly, an O-form model with moderation indicates a significantly negative relationship between LPRO and LTEE, while the coefficient of LPRO2 is positive and significant. These coefficients substantiate a concave upward relationship between overall eco-efficiency and extraordinary economic potential.

These findings reveal that extraordinary economic potential negatively impacts overall eco-efficiency during early growth stages due to composition and scale effects. However, as growth progresses, LPRO fosters improvements in overall eco-efficiency due to the technique effect. Extraordinary economic potential plays a pivotal role in overall eco-efficiency through its connection with natural resources. In alignment with Sustainable Development Goal (SDG) 12, PRO must be decoupled from overexploitation and overuse of natural resources to address ecological degradation.

S-form models, with and without moderation, further support a U-type relationship between extraordinary economic potential and services eco-efficiency. This result aligns with findings from Madaleno et al. (2023), Xie et al. (2023), and Borowiec and Papież (2024), who highlighted that income drives ecological sustainability while mitigating ecological intensity at later stages of growth. Notably, Xie et al. (2023) examined the ecological impact of economic growth among OECD members and found no evidence to validate the Environmental Kuznets Curve (EKC) concept during the period from 1990 to 2020. Similarly, Ahmad and Jabeen (2024) concluded that economic growth significantly enhances the eco-efficiency of European Union members in the long run.

4.2.2. Energy transition and eco-efficiency

Our findings reveal that energy transition enhances the overall eco-efficiency of OECD members, as evidenced by the O-form models. In the model without a joint effect, the coefficient of **LTRA** is statistically significant and positive across the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles. Table 7 displays a decreasing trend while maintaining a positive relationship between **LTEE** and **LTRA**. The favourable ecological impact of energy transition can be attributed to its role in reducing the harmful pollutants emitted by fossil fuels as economies shift from non-renewable to green energy sources. With stricter environmental regulations, eco-unfriendly businesses are incentivized to adopt eco-friendly innovations. Furthermore, energy transition encourages nations to achieve energy efficiency, thus supporting reductions in industrial greenhouse gas emissions (Bergougui, 2024b).

These findings align with Jiang et al. (2022), who concluded that a swift transition to clean energy effectively reduces pollutants and improves eco-efficiency. Similarly, Bergougui (2024b), Bergougui et al. (2024), Bergougui (2024c), and Ullah et al. (2023b) highlighted that investments in renewable energy technologies bolster ecological sustainability in developed nations. Yadav et al. (2023) further underscored the environmental benefits of energy transition in mitigating anthropogenic emissions and advancing climate change mitigation efforts. Akpanke et al. (2024) found that renewable energy transformation fosters sustainable structural development and alleviates ecological stress. Akram et al. (2023) also reported that renewable energy plays a pivotal role in replacing dirty energy sources, reducing the dominance of

Table 7
Feedback on elasticity coefficients (ESDK and MACS, LTEE and LSEE- response variables).

Model	Var./Quat.	ESDK	0.1	0.3	0.5	0.7	0.9
Model 1	LPRO	−9.414a	−7.361a	−8.429a	−9.180a	−10.232a	−11.661a
	LPRO^2	0.471a	0.369a	0.422a	0.459a	0.511a	0.582a
	LTRA	0.095b	0.112a	0.103a	0.097a	0.088a	0.076c
	LETG	0.081a	0.094a	0.087a	0.083a	0.076a	0.067b
	LRD	0.266a	0.189	0.229a	0.258a	0.297a	0.351b
	LEUM	−0.055a	−0.077a	−0.066a	−0.058a	−0.046a	−0.031
	LTRD	0.182a	0.213a	0.197a	0.186a	0.170a	0.148c
Model 2	LPRO	−10.056a	−8.267a	−9.174a	−9.867a	−10.851a	−12.047a
	LPRO2	0.495a	0.404a	0.450a	0.485a	0.535a	0.595a
	LTRA	0.113b	0.114a	0.114a	0.113a	0.113a	0.112b
	LETG	0.119a	0.145a	0.132a	0.121a	0.107a	0.089b
	LRD	0.327a	0.301b	0.314a	0.325a	0.339a	0.357c
	LEUM	−0.058a	−0.074a	−0.066a	−0.060a	−0.051a	−0.040c
	LTRD	0.185a	0.204a	0.194a	0.187a	0.177a	0.164c
Model 3	LPRO	−9.414a	−7.361a	−8.429a	−9.180a	−10.232a	−11.661a
	LPRO2	0.471a	0.369a	0.422a	0.459a	0.511a	0.582a
	LTRA	0.095a	0.112a	0.103a	0.097a	0.088a	0.076c
	LMod	0.081a	0.094a	0.087a	0.083a	0.076a	0.067b
	LRD	0.266a	0.189	0.229a	0.258a	0.297a	0.351b
	LEUM	−0.136a	−0.171a	−0.153a	−0.140a	−0.122a	−0.098a
	LTRD	0.182a	0.213a	0.197a	0.186a	0.170a	0.148c
Model 4	LPRO	−10.056a	−8.267a	−9.174a	−9.867a	−10.851a	−12.047a
	LPRO2	0.495a	0.404a	0.450a	0.485a	0.535a	0.595a
	LTRA	0.113a	0.114a	0.114a	0.113a	0.113a	0.112b
	LMod	0.119a	0.145a	0.132a	0.121a	0.107a	0.089b
	LRD	0.327a	0.301b	0.314a	0.325a	0.339a	0.357c
	LEUM	−0.177a	−0.220a	−0.198a	−0.182a	−0.158a	−0.130a
	LTRD	0.185a	0.204a	0.194a	0.187a	0.177a	0.164c

Note: p values underlined, a – $p < 1$ %; b – $p < 5$ %; c – $p < 10$ %; Mod = ETG*EUM; Quantiles (0.1–0.9).

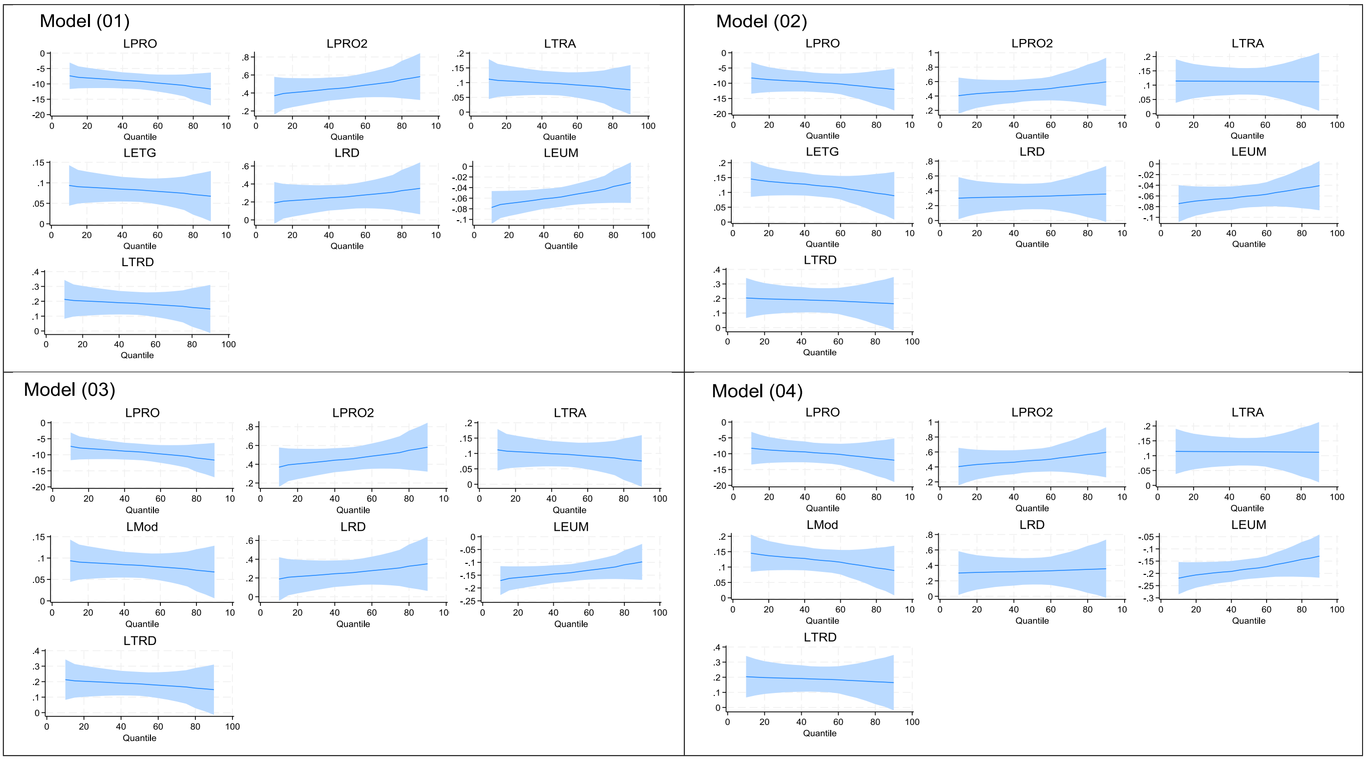


Fig. 2. Synopsis of MACS outcomes (LTEE and LSEE- response variables).

oil, coal, and natural gas in the global energy mix.

The S-form models, with and without moderation, corroborate the O-form model findings, confirming that energy transition improvements act as an effective strategy to enhance the eco-efficiency of OECD members.

4.2.3. Environmental governance and eco-efficiency

The coefficient of environmental governance is both positive and significant, with a decreasing trend in the O-form model without moderation, indicating that effective environmental governance improves overall eco-efficiency. Policymakers achieve this by imposing stringent environmental regulations to curb eco-unfriendly behavior among individuals and businesses. For instance, "stick" policy measures, such as higher taxes on ecological damages, increase the costs of harmful practices. Consequently, environmental governance is a critical tool in managing eco-intensity to achieve OECD eco-efficiency objectives.

Effective ecological governance addresses the adverse environmental impacts of economic activities by stimulating research and development subsidies for green innovations. Its ultimate aim is to mitigate the environmental side effects of economic processes by promoting clean energy transition, sustainable resource extraction, and conservation practices. Since markets alone may not resolve rising ecological pressures, governments play a crucial role in enhancing the eco-efficiency of OECD members.

Xie et al. (2023) provided similar evidence, demonstrating that environmental governance effectively reduces pollutant emissions in OECD countries. Ullah et al. (2023a) emphasized the role of governance in fostering ecological sustainability by supporting clean energy transitions. Similarly, Borowiec and Papież (2024) found that environmental governance is pivotal in addressing ecological deterioration. Zou and Wang (2024) highlighted that governance spurs ecological and economic improvements in firms via innovation and renewable energy adoption.

While these results are consistent with many prior studies, they diverge from Danish and Ulucak (2023), who argue that environmentally friendly policies may increase production costs, potentially discouraging resource-intensive economic activities. This divergence highlights the complexity of the relationship between governance and eco-efficiency, warranting a closer examination of the contextual factors and underlying mechanisms. Danish and Ulucak (2023) explored the interactions between natural resource rents, economic growth, and environmental technologies in the United States, highlighting that stringent environmental policies could raise production costs, thereby creating economic trade-offs for industries heavily reliant on natural resource extraction. These findings suggest that the costs of transitioning to environmentally sustainable practices might outweigh the perceived benefits in the short term, particularly in economies with high resource dependency. Increased costs could arise from compliance with stricter regulations, investments in cleaner technologies, or shifts in production processes, all of which may reduce immediate economic efficiency. However, such short-term trade-offs do not necessarily negate the long-term benefits of environmental governance. As evidenced in this study, the positive impacts of ETG on overall and services-related eco-efficiency (especially in the S-form model without moderation) may reflect the ability of well-designed governance frameworks to align economic incentives with environmental objectives over time. By fostering innovation and promoting sustainable practices, these policies can reduce the environmental footprint of economic activities and enhance eco-efficiency in the long run.

The divergence between this study's findings and those of Danish and Ulucak (2023) can be attributed to several contextual and methodological factors. First, the differences in geographical and economic contexts play a significant role; while Danish and Ulucak (2023) focus on the United States—a resource-rich, high-income country—this study examines OECD members with varying levels of eco-efficiency and governance structures, which can lead to differing outcomes. Second, the design and implementation of environmental policies matter significantly. Policies that impose strict regulations without offering incentives, such as subsidies or tax credits for adopting cleaner technologies, may increase production costs and discourage compliance, as observed in Danish and Ulucak (2023). Conversely, well-balanced policies that align economic incentives with environmental goals tend to enhance eco-efficiency. Third, the temporal dimension is critical; Danish and Ulucak (2023) highlight short-term trade-offs associated with governance, whereas this study may capture long-term benefits, including enhanced resource efficiency and innovation. Lastly, sectoral dynamics contribute to the discrepancies, as the S-form model in this study shows that service sectors, being less resource-intensive, adapt more easily to governance policies compared to heavy industries, which may face higher transition costs. These factors collectively highlight the need for tailored and context-sensitive environmental governance strategies.

4.2.4. Research and development (R&D) intensity and eco-efficiency

Research and development (R&D) intensity positively influences overall eco-efficiency in both O-form models, with and without moderation. Table 7 and Fig. 2 show statistically significant and positive coefficients of R&D intensity across the 10th to 90th quantiles, revealing an increasing trend of influence from lower to higher quantiles. This demonstrates that as countries improve their eco-efficiency levels, the contribution of R&D becomes increasingly impactful.

The eco-efficiency benefits of R&D stem from its ability to drive innovation, helping industries adopt cleaner production methods, reduce waste, and conserve energy. R&D also encourages the development of new materials and technologies that reduce dependency on scarce resources. For example, Akram et al. (2023) demonstrated that innovation is a viable means of addressing ecological challenges, such as greenhouse gas emissions and the overexploitation of natural resources. Ullah et al. (2023b) further emphasized that innovation fosters cleaner energy transitions, supporting ecological sustainability. Similarly, Shahid et al. (2024) highlighted that R&D has been pivotal in meeting China's eco-efficiency targets, especially in renewable energy technologies.

In OECD countries, R&D initiatives have yielded notable eco-efficiency improvements. For instance, Denmark's investment in wind energy R&D has positioned it as a global leader in renewable energy technologies. Germany's "Energiewende" policy, underpinned by substantial R&D in solar and wind energy, has significantly reduced its energy-related emissions. In the service sector, Sweden's advancements in smart grid technologies and digital innovations have enhanced energy efficiency and resource utilization. These examples demonstrate the critical role of targeted R&D investments in addressing specific ecological challenges and achieving eco-efficiency gains.

The S-form models, with and without moderation, confirm these findings, showing that R&D intensity reduces service-related eco-intensity and enhances the eco-efficiency of OECD members. Service industries, being less resource-intensive, often benefit more directly from innovations in digitalization, logistics, and energy-efficient infrastructure. Policymakers can draw on these successful examples to prioritize R&D funding and design policies that incentivize innovation tailored to both industrial and service sectors, thereby achieving long-term ecological sustainability.

4.2.5. International trade and eco-efficiency

Table 7 and Fig. 2 demonstrate that international trade, measured as a percentage of GDP, positively impacts overall eco-efficiency in the O-form model without moderation. The findings indicate a significant and positive relationship between trade and eco-efficiency across quantiles, though the effect decreases from lower to upper quantiles. Trade (% of GDP) reduces ecological intensity in OECD members, particularly in countries with lower eco-efficiency levels.

Dai and Du (2023) provided similar findings, showing that international trade enhances ecological sustainability when stringent environmental policies are in place. Cheng et al. (2022) advocated that trade facilitates a shift towards clean energy and sustainable resource utilization. Ahmad and Satrovic (2023) observed that trade improves environmental sustainability within the Group of Seven (G7) nations.

However, contrasting evidence from Ahmad and Jabeen (2024) highlighted the destructive ecological impact of trade in the European Union, where increased industrial activities fueled by trade exacerbate ecological pressures. Both S-form models confirm the critical role of trade in achieving service-related eco-efficiency goals for OECD members.

4.2.6. Excess use of natural resources (EUM) and eco-efficiency

The excess use of natural resources (EUM) hinders the achievement of overall and service-related eco-efficiency in OECD members, as evidenced by the negative and statistically significant coefficients of **LEUM** in models without moderation. The coefficients of EUM on total eco-efficiency (TEE) rise from −0.077 % in the 10th quantile to −0.031 % in the 90th quantile. For service eco-efficiency (SEE), the coefficients increase from −0.074 % to −0.040 % over the same quantiles.

These results align with Fang et al. (2024), who emphasized that over-reliance on natural resources contributes to ecological degradation. Danish and Ulucak, 2023 and Ni et al. (2022) reported similar findings, showing that lax environmental regulations, innovation deficits, and unstable resource prices exacerbate environmental deterioration. However, studies such as Ullah et al. (2023a) and Khan et al. (2023) suggested that natural resource rents could be utilized to protect the environment in economically stable countries.

4.2.7. Joint impact of ETG and EUM on eco-efficiency

The interaction term of environmental governance (ETG) and excessive natural resource use (EUM) reveals a positive and significant impact on overall and service-related eco-efficiency across all quantiles in both O-form and S-form models with moderation. The positive coefficient suggests that robust environmental governance plays a crucial role in mitigating the negative ecological consequences associated with excessive natural resource use. This effect is particularly evident in countries with lower levels of eco-efficiency, where governance mechanisms are vital to promoting sustainability.

Environmental governance appears to enhance natural resource efficiency by enforcing policies and measures that curb overexploitation. For instance, stringent regulations, such as carbon taxes, subsidies for cleaner technologies, and incentives for resource-efficient practices, could limit excessive resource extraction and encourage the adoption of sustainable alternatives. These mechanisms create a regulatory framework that aligns economic activities with environmental goals, fostering eco-efficiency across sectors.

Previous studies align with these findings. For example, Ali et al. (2022a) identified the moderating effects of environmental governance in reducing ecological footprints, emphasizing its role in promoting sustainable resource management. Similarly, Ullah et al. (2023b) demonstrated that stringent governance policies effectively limit the detrimental effects of resource overuse, highlighting the importance of regulatory measures in achieving long-term environmental sustainability.

Moreover, the joint moderating effects underscore the significance of integrating environmental governance with natural resource policies. Countries with higher eco-efficiency levels may already benefit from advanced governance frameworks, but the findings indicate that even in resource-intensive economies, adopting stringent governance mechanisms can facilitate the transition towards more sustainable practices. As outlined by SDG-12, ensuring sustainable production and consumption patterns requires targeted interventions, including regulatory oversight and market-based incentives, to optimize resource use and reduce environmental impacts.

Finally, Table 8 provides a concise summary of all the key results, consolidating the insights from both O-form and S-form models, and highlighting the intricate relationships between extraordinary economic potential, eco-efficiency, and their moderating factors.

Table 8
Summary of key trends.

Variable	Impact on Eco-Efficiency	Key Insight
Extraordinary Economic Potential (PRO)	Concave upward (O-form), U-shaped (S-form)	Early stages: negative impact; later stages: positive impact due to technique effect.
Energy Transition (LTRA)	Positive and significant	Shift to renewable energy reduces emissions and promotes eco-friendly innovations.
Environmental Governance (ETG)	Positive and significant	Stringent policies and green innovation mitigate ecological pressures.
RD Intensity	Positive and significant	Innovation drives waste management and energy conservation, enhancing eco-efficiency.
International Trade	Positive and significant	Trade promotes sustainability when coupled with strong environmental policies.
Excess Use of Natural Resources (EUM)	Negative and significant	Over-reliance on natural resources exacerbates ecological degradation.
ETG-EUM Interaction	Positive and significant	Environmental governance mitigates the adverse effects of excess natural resource use.

4.3. Sensitivity analysis

4.3.1. Supplementary proxy: Import diversification index

The sensitivity analysis of our main findings is grounded on the deliberation of supplementary proxy for the economic importance of international trade namely, import diversification index in Table A1 and Fig. A1. The O-form and S-form models without moderation reach the conclusion that energy transition, research and development intensity, and environmental governance matter in achieving the eco-efficiency targets of OECD members. Our outcomes propose the U-type association between extraordinary economic potential and eco-efficiency such that PRO facilitates the eco-intensity in the early stages of growth while it results in the improvements of eco-efficiency in the later stages. In line with our main findings, import diversification index encourages the eco-efficiency of the inspected sample. An explanation is that developed countries may accelerate the imports of dirty products to reduce emission-intensive industries and energy-related anthropogenic emissions. As such, import diversification takes a prominent role in tackling the environmental pressure of OECD members as proposed by (Doğan et al., 2022). In the same fashion, Madaleno et al. (2023) advocated the outcome that import eases the access to intermediate items which are responsible for ecological sustainability if harmonized with environmental regulations. The O-form and S-form models with moderation express a positive and statistically significant coefficient of interaction terms, rendering the overall and services eco-efficiency enhancement effect of EUM via the channel of environmental governance.

Despite that the investigated OECD members are among the most industrialized countries globally, the present study fails to assess the impacts of various independent variables on the industrial eco-efficiency in addition to service- and total eco-efficiency. This is due to the missing values in industry (including construction), value added time-series for the United States. It would be of vital importance to delve into the impacts of independent variables on industrial eco-efficiency as boosted industry encouraged by international trade lifts up the consumption of materials from nature, and posits an adverse ecological impact. The analysis of the determinants of industry eco-efficiency is outstandingly prominent as industry sector may exhibit the moderation impact of environmental governance interaction with EUM dissimilar to the service sector and provide a foundation for plausible policy directions.

4.3.2. Alternative econometric technique: Driscoll-Kraay (ESDK)

Finally, to authenticate the findings of MACS estimator, this study builds upon the Driscoll-Kraay (ESDK) econometric technique. As seen in Tables 7 and A1, the O-form and S-form models without moderation suggest statistically significant and positive nexus amid energy transition, research and development intensity, the economic importance of international trade and environmental governance foster the overall and services eco-efficiency of OECD nations. Notably, a 1 % increase in energy transition, matters for the rise of eco-efficiency by 0.095 % (Models 1&3), 0.113 % (Models 2&4), 0.105 % (Models 5&7) and 0.118 % (Models 6&8), respectively. The coefficient of ETG advocated that a 1 % rise of environmental governance, results in a 0.081 % (Model 1), 0.119 % (Model 2), 0.054 % (Model 5) and 0.083 % (Model 6) rise in eco-efficiency in models without moderation. Given the coefficients of EUM, excess use of natural resources is responsible for the impediment of OECD's eco-efficiency such that a 1 % rise in EUM reduces TEE and SEE by 0.055 % (Model 1), 0.058 % (Model 2), 0.136 % (Model 3), 0.177 % (Model 4), 0.033 % (Model 5), 0.034 % (Model 6), 0.087 % (Model 7), and 0.117 % (Model 8) respectively. The outcomes of research and development intensity showed that RD matters for ecological betterment of OECD members. In the same vein, both proxies for the economic importance of international trade insinuate the beneficial ecological impact of international trade in the context of OECD nations. The models with moderation advocated that EUM matters for the improvement of overall and services eco-efficiency through the ecological governance channel. The twin robustness check, based on the supplementary regressor (Table A1 and Fig. A1) and alternative econometric technique (Tables 7 and A1), render the support for our main findings (Tables 7 and A1). Hence, it can be deduced that our main findings are plausible to develop policy implications for eco-efficient future of OECD members.

5. Conclusion, policy implications, limitations and recommendations for future research

5.1. Conclusion

This study contributes to the existing literature by examining the relationship between the excess use of natural resources, environmental governance, and eco-efficiency in developed economies. Specifically, it addresses a critical gap in the current research by investigating the potential mitigating effects of effective ETG on the ecological pressures exerted by excess natural resource consumption. Employing MACS, this research analyzed data from nine OECD countries over the period 1997–2020. The findings reveal a nuanced relationship between extraordinary economic potential (PRO) and eco-efficiency, characterized by a concave upward pattern. Moreover, the study provides empirical evidence that energy transition, ETG, research and development intensity, and the economic importance of international trade positively influence eco-efficiency in the studied countries. Conversely, EUM was found to negatively impact eco-efficiency, exacerbating ecological pressures. Notably, the research demonstrates that ETG acts as a positive moderator on the relationship between EUM and eco-efficiency, with this effect being more pronounced in less eco-efficient nations. The robustness of these results is confirmed through alternative eco-efficiency measures (e.g., services eco-efficiency), an additional proxy for trade (import diversification index - DI), and alternative econometric methods. These findings underscore the importance of implementing robust environmental policies in OECD countries to promote sustainable resource extraction and improve eco-efficiency.

5.2. Policy implications

The findings of this study, coupled with external data, underscore the critical need for comprehensive environmental policies in OECD countries to enhance eco-efficiency while managing natural resource use. Accelerating energy transition should be a priority, as renewable energy sources have shown significant growth potential. According to the

International Energy Agency (IEA), renewable energy capacity additions in OECD countries increased by 13 % in 2021, reaching almost 160 GW. This trend aligns with our finding that energy transition positively impacts eco-efficiency. Environmental governance must be strengthened, considering that OECD countries collectively account for approximately 40 % of global CO2 emissions (WB, 2023). Our study shows that improved environmental governance positively moderates the impact of excess resource use on eco-efficiency, especially in less eco-efficient nations. Investment in research and development is crucial. OECD data indicates that average R&D intensity (gross domestic expenditure on R&D as a percentage of GDP) across OECD countries was 2.68 % in 2021. Countries should aim to meet or exceed this average, given our finding that R&D intensity advances eco-efficiency. Policymakers should also consider the role of international trade in eco-efficiency. The OECD reports that its members accounted for 61 % of global trade in 2022. Trade policies should be crafted with environmental considerations in mind, potentially including eco-efficiency standards in trade agreements. Sustainable resource management is imperative, as the global material footprint per capita in high-income countries was 26.3 metric tons in 2019 (UN SDG Report 2022), far exceeding sustainable levels. Our study shows that excess use of natural resources negatively impacts eco-efficiency, highlighting the need for waste-free extraction policies and circular economy approaches. To achieve long-term improvements in eco-efficiency, policymakers should ensure policy consistency, foster international cooperation, and implement robust monitoring systems. The OECD Better Life Index shows that 69 % of people in OECD countries trust their national government, suggesting a strong foundation for implementing these evidence-based policy recommendations. By adopting these measures, OECD countries can make significant strides towards balancing economic growth with ecological sustainability, contributing to the achievement of the Sustainable Development Goals (SDGs).

5.3. Limitations and recommendations for future research

This study, while providing valuable insights into eco-efficiency in OECD countries, has several limitations that future research should address. Firstly, the focus on specific variables may have overlooked nuances in energy intensity and economic complexity types. Future studies should explore various energy intensity metrics and economic complexity indices to test the consistency of results across different measures. Secondly, the impact of diverse national characteristics on eco-efficiency, such as demographics, climate conditions, population density, urbanization rates, and industrialization levels, warrants further investigation. These factors could reveal important contextual moderators of the main effects found in this study. Additionally, while the research touched on energy transition, it could benefit from more explicit integration with other pressing global challenges like population growth, global warming, and economic development, providing a more holistic view of eco-efficiency within sustainable development contexts. The study's timeframe (1997–2020) may not capture very long-term trends or recent developments, suggesting a need for longer longitudinal studies and comparative analyses between OECD and non-OECD countries. Future research should also evaluate the effectiveness of implemented environmental policies on eco-efficiency, potentially using quasi-experimental designs. Sector-specific eco-efficiency dynamics and the role of specific technological innovations (e.g., AI, blockchain) in enhancing eco-efficiency are areas ripe for further exploration. Lastly, incorporating circular economy principles more fully into the eco-efficiency framework and developing metrics that capture circularity alongside efficiency could provide valuable new perspectives. By addressing these limitations and pursuing these research directions, future studies can build upon the current findings to offer a more comprehensive understanding of eco-efficiency dynamics in developed economies, crucial for informing evidence-based policies aimed at achieving sustainable development goals while effectively managing natural resource use.

CRediT authorship contribution statement

Brahim Bergougui: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Formal analysis, Conceptualization. **Elma Satrovic:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Appendix

Table A1
Feedback on robustness inspection (ESDK and MACS, LTEE and LSEE- response variables).

Model	Var./Quat	ESDK	0.1	0.3	0.5	0.7	0.9
Model 5	LPRO	−7.989a	−7.121a	−7.638a	−8.008a	−8.326a	−8.937a
	LPRO2	0.409a	0.365a	0.391a	0.410a	0.426a	0.457a
	LTRA	0.105a	0.114a	0.109a	0.105a	0.102a	0.096b
	LETG	0.054a	0.056c	0.055a	0.054a	0.054a	0.052
	LRD	0.268a	0.279b	0.272a	0.268a	0.264a	0.256c
	LEUM	−0.033a	−0.046a	−0.038a	−0.032a	−0.027b	−0.017
	LDI	0.223a	0.257b	0.237a	0.222a	0.210a	0.186
Model 6	LPRO	−7.998a	−6.980b	−6.980b	−7.943a	−8.465a	−9.155a
	LPRO2	0.404a	0.351b	0.351b	0.401a	0.428a	0.463a
	LTRA	0.118a	0.109a	0.109a	0.118a	0.122a	0.128b
	LETG	0.083a	0.098a	0.098a	0.084a	0.076a	0.065
	LRD	0.337a	0.381b	0.381b	0.340a	0.317a	0.288
	LEUM	−0.034a	−0.045b	−0.045b	−0.035a	−0.029b	−0.021
	LDI	0.305a	0.336a	0.336a	0.307a	0.291a	0.270c
Model 7	LPRO	−7.989a	−7.121a	−7.638a	−8.008a	−8.326a	−8.937a
	LPRO2	0.409a	0.365a	0.391a	0.410a	0.426a	0.457a
	LTRA	0.105a	0.114a	0.109a	0.105a	0.102a	0.096b

(*continued on next page*)

Table A1 (*continued*)

Model	Var./Quat	ESDK	0.1	0.3	0.5	0.7	0.9
	LMod	0.054a	0.056c	0.055a	0.054a	0.054a	0.052
	LRD	0.268a	0.279b	0.272a	0.268a	0.264a	0.256c
	LEUM	−0.087a	−0.103a	−0.093a	−0.086a	−0.081a	−0.069c
	LDI	0.223a	0.257b	0.237a	0.222a	0.210a	0.186
	LPRO	−7.998a	−6.980b	−7.544a	−7.943a	−8.465a	−9.155a
	LPRO2	0.404a	0.351b	0.380a	0.401a	0.428a	0.463a
	LTRA	0.118a	0.109a	0.114a	0.118a	0.122a	0.128b
Model 8	LMod	0.083a	0.098a	0.090a	0.084a	0.076a	0.065
	LRD	0.337a	0.381b	0.357a	0.340a	0.317a	0.288
	LEUM	−0.117a	−0.144a	−0.129a	−0.118a	−0.104a	−0.086c
	LDI	0.305a	0.336a	0.319a	0.307a	0.291a	0.270c

Note: p values underlined, a – p < 1 %; b – p < 5 %; c – p < 10 %; Mod = ETG*EUM; Quantiles (0.1–0.9).

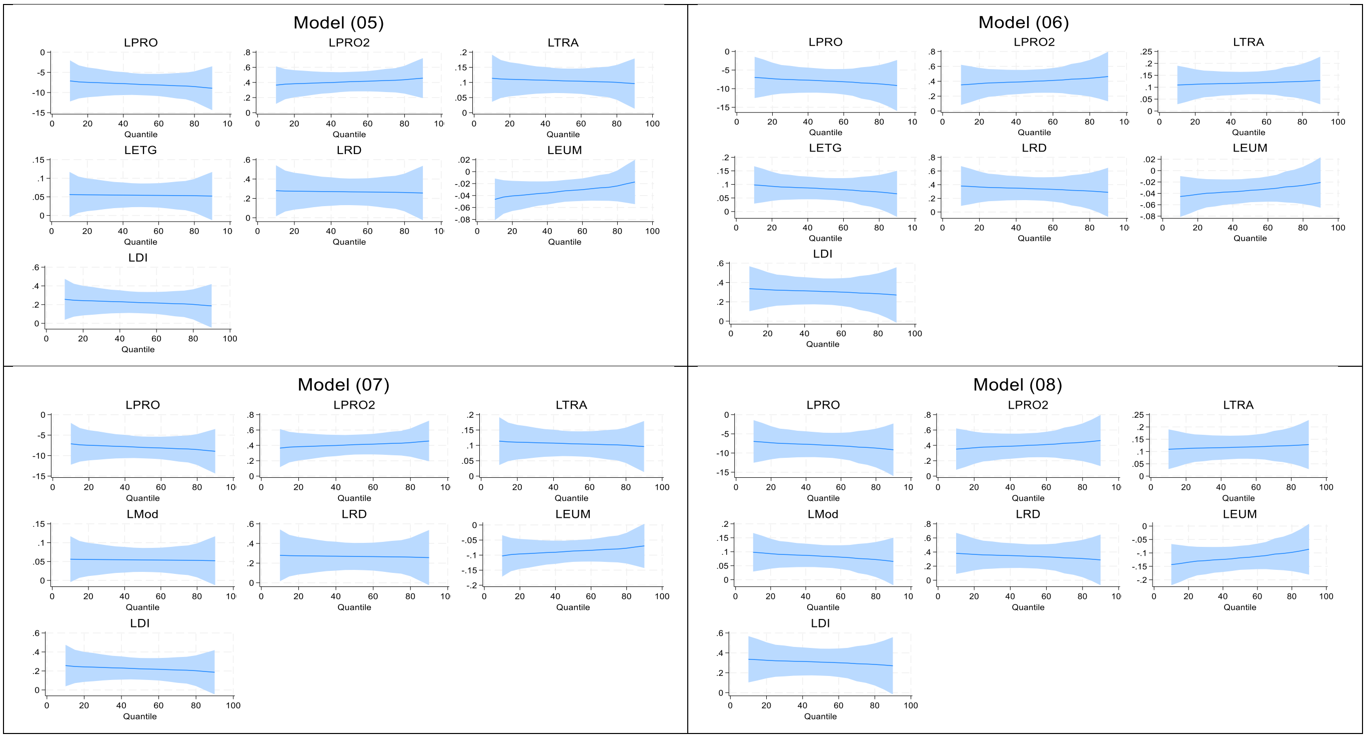


Fig. A1. Synopsis of MACS outcomes – robustness inspection (LTEE and LSEE- response variables).

Data availability

The Stata code and datasets utilized in this study can be accessed through the GitHub repository maintained by Brahim Bergougui, located at https://github.com/BrahimBergougui/data-and-code

References

Ahmad, A., Jabeen, G., 2024. Relating economic openness and export diversification to eco-efficiency: is green innovation critical? Int. J. Financ. Econ. https://doi.org/10.1002/ijfe.2825.

Ahmad, M., Satrovic, E., 2023. How does monetary policy moderate the influence of economic complexity and technological innovation on environmental sustainability? The role of green central banking. Int. J. Financ. Econ. 1–28. https://doi.org/10.1002/ijfe.2872.

Ahmad, M., Satrovic, E., 2024. Modeling natural resources for ecological sustainability. Gondwana Res. 126 (February 2024), 243–266. https://doi.org/10.1016/j.gr.2023.09.015.

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

Ahmed, K., 2020. Environmental policy stringency, related technological change and emissions inventory in 20 OECD countries. J. Environ. Manag. 274. https://doi.org/10.1016/j.jenvman.2020.111209.

Akpanke, T.A., Deka, A., Ozdeser, H., Seraj, M., 2024. Ecological footprint in the OECD countries: do energy efficiency and renewable energy matter? Environ. Sci. Pollut. Res. 31 (10), 15289–15301. https://doi.org/10.1007/s11356-024-32151-1.

Akram, R., Ibrahim, R.L., Wang, Z., Adebayo, T.S., Irfan, M., 2023. Neutralizing the surging emissions amidst natural resource dependence, eco-innovation, and green energy in G7 countries: insights for global environmental sustainability. J. Environ. Manag. 344, 118560. https://doi.org/10.1016/j.jenvman.2023.118560.

Alfalih, A.A., Hadj, T.B., 2022. Financialization, natural resources rents and environmental sustainability dynamics in Saudi Arabia under high and low regimes. Res. Pol. https://doi.org/10.1016/j.resourpol.2022.102593.

Ali, K., Jianguo, D., Kirikkaleli, D., 2022a. Modeling the natural resources and financial inclusion on ecological footprint: the role of economic governance institutions. Evidence from ECOWAS economies. Res. Pol. 79, 103115. https://doi.org/10.1016/j.resourpol.2022.103115.

Ali, M., Kirikkaleli, D., Sharma, R., Altuntaş, M., 2022b. The nexus between remittances, natural resources, technological innovation, economic growth, and environmental sustainability in Pakistan. Environ. Sci. Pollut. Res. 29. https://doi.org/10.1007/s11356-022-21228-4.

Apostu, S.A. Valentina, Vasile, Mirela Panait, Sava, Valentin, 2023. Exploring the ecological efficiency as the path to resilience. Econ. Res. Ekonomska Istraživanja 36, 2. https://doi.org/10.1080/1331677X.2022.2108476.

Arjun, Mishra, B.R., 2024. Asymmetric role of environmental policy stringency,fiscal, and monetary policy on environmental sustainability: evidence from BRICS-T countries. Nat. Res. Forum 1–32. https://doi.org/10.1111/1477-8947.12434.

Bergougui, B., 2024a. Algeria׳s pathway to COP28 and SDGs: asymmetric impact of environmental technology, energy productivity, and material resource efficiency on environmental sustainability. Energ. Strat. Rev. 55, 101541. https://doi.org/10.1016/j.esr.2024.101541.

Bergougui, B., 2024b. Investigating the relationships among green technologies, financial development and ecological footprint levels in Algeria: evidence from a novel fourier ARDL approach. Sustain. Cities Soc. 112, 105621. https://doi.org/10.1016/j.scs.2024.105621.

Bergougui, B., 2024c. Moving toward environmental mitigation in Algeria: asymmetric impact of fossil fuel energy, renewable energy and technological innovation on CO2 emissions. Energ. Strat. Rev. 51, 101281. https://doi.org/10.1016/j.esr.2023.101281.

Bergougui, B., Aldawsari, M.I., 2024. Asymmetric impact of patents on green technologies on Algeria's ecological future. J. Environ. Manag. 355, 120426. https://doi.org/10.1016/j.jenvman.2024.120426.

Bergougui, B., Meziane, S., 2025. Assessing the impact of green energy transition, technological innovation, and natural resources on load capacity factor in Algeria: evidence from dynamic autoregressive distributed lag simulations and machine learning validation. Sustainability 17 (5), 1815. https://doi.org/10.3390/su17051815.

Bergougui, B., Murshed, S.M., 2020. New evidence on the oil-democracy nexus utilising the varieties of democracy data. Res. Policy 69, 101905. https://doi.org/10.1016/j.resourpol.2020.101905.

Bergougui, B., Murshed, S.M., 2021. Revisiting the oil wealth-growth nexus: the role of economic norms in avoiding the oil curse. Extr. Ind. Soc. 8 (3), 100929. https://doi.org/10.1016/j.exis.2021.100929.

Bergougui, B., Murshed, S.M., 2023. Aggregate and disaggregate impact of natural resources on sustainable development: new evidence from the latest institutional data. Environ. Sustain. Indic. 20, 100302. https://doi.org/10.1016/j.indic.2023.100302.

Bergougui, B., Mehibel, S., Boudjana, R.H., 2024. Asymmetric nexus between green technologies, economic policy uncertainty, and environmental sustainability: evidence from Algeria. J. Environ. Manag. 360, 121172. https://doi.org/10.1016/j.jenvman.2024.121172.

Bergougui, B., Murshed, S.M., Shahbaz, M., Zambrano-Monserrate, M.A., Samour, A., Aldawsari, M.I., 2025. Towards secure energy systems: examining asymmetric impact of energy transition, environmental technology and digitalization on Chinese city-level energy security. Renew. Energy 238, 121883. https://doi.org/10.1016/j.renene.2024.121883.

Bhowmik, R., Sharif, A., Anwar, A., Syed, Q.R., Cong, P.T., Ha, N.N., 2024. Does environmental policy stringency alter the natural resources-emissions nexus? Evidence from G-7 countries. Geosci. Front. https://doi.org/10.1016/j.gsf.2024.101874, 101874.

Borowiec, J., Papież, M., 2024. Convergence of CO2 emissions in countries at different stages of development. Do globalisation and environmental policies matter? Energy Policy 184 (January 2024), 113866. https://doi.org/10.1016/j.enpol.2023.113866.

Chang, G., Yasin, I., Naqvi, S.M.M.A., 2024. Environmental sustainability in OECD nations: the moderating impact of green innovation on urbanization and green growth. Sustainability 16 (16), 7047. https://doi.org/10.3390/su16167047.

Chen, F., Ahmad, S., Arshad, S., Ali, S., Rizwan, M., Hamzah Saleem, M., Driha, O.M., Balsalobre-Lorente, D., 2022. Towards achieving eco-efficiency in top 10 polluted countries: the role of green technology and natural resource rents. Gondwana Res. 110, 114–127. https://doi.org/10.1016/j.gr.2022.06.010.

Cheng, H., Liu, X., Xu, Z., 2022. Impact of carbon emission trading market on regional urbanization: an empirical study based on a difference-in-differences model. Econ. Anal. Lett. 1. https://doi.org/10.58567/eal01010003.

Dai, S., Du, X., 2023. Discovering the role of trade diversification, natural resources, and environmental policy stringency on ecological sustainability in the BRICST region. Res. Policy 85 (Part B), 103868. https://doi.org/10.1016/j.resourpol.2023.103868.

Danish, R., Ulucak, M.A., 2023. Baloch an empirical approach to the nexus between natural resources and environmental pollution: do economic policy and environmental-related technologies make any difference? Res. Policy 81, 103361. https://doi.org/10.1016/j.resourpol.2023.103361.

Doğan, B., Ferraz, D., Gupta, M., Huynh, T.L.D., Shahzadi, I., 2022. Exploring the effects of import diversification on energy efficiency: evidence from the OECD economies renew. Energy 189, 639–650. https://doi.org/10.1016/j.renene.2022.03.018.

Doğan, B, Khalfaoui, R, Bergougui, B., Ghosh, S., 2025. Unveiling the Impact of the digital economy on the Interplay of energy transition environmental transformation, and renewable energy adoption. Res. Int. Bus. Financ. 102837. https://doi.org/10.1016/j.ribaf.2025.102837.

Dong, K., Sun, R., Dong, X., 2018. CO2 emissions, natural gas and renewables, economic growth: assessing the evidence from China. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2018.05.322.

Erdoğan, S., Çakar, N.D., Ulucak, R., Kassouri, Y., 2021. The role of natural resources abundance and dependence in achieving environmental sustainability: evidence from resource-based economies. Sustain. Dev. 29.

Fang, X., Khalaf, O.I., Guanglei, W., Cristia, J.F.E., Almasabi, S., 2024. Exploring impact of green finance and natural resources on eco-efficiency: case of China. Sci. Rep. 14 (1), 20153. https://doi.org/10.1038/s41598-024-70993-4.

Georgatzi, V.V., Stamboulis, Y., Vestikas, A., 2020. Examining the determinants of CO2 emissions caused by the transport sector: empirical evidence from 12 European countries. Econ. Anal. Pol. 65. https://doi.org/10.1016/j.eap.2019.11.003.

GFN, 2022. Global footprint network: advancing the science of sustainability [WWW document]. In: Natl. Footpr. Biocapacity Accounts. URL. https://www.footprintnetwork.org/resources/data (accessed 30.7.23).

Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. Q. J. Econ. 110 (2), 353–377.

Guo, Y., Alnafrah, I., Hou, X., 2024. How natural resources and technological advancements affect environmental quality: Evidence from load capacity factor in N-11 nations. Nat. Resour. Foru. https://doi.org/10.1111/1477-8947.12442.

He, Y., Li, X., Huang, P., Wang, J., 2022. Exploring the road toward environmental sustainability: natural resources, renewable energy consumption, economic growth, and greenhouse gas emissions. Sustainability 14. https://doi.org/10.3390/su14031579.

Hickel, J., O'Neill, D.W., Fanning, A.L., H., 2022. Zoomkawala national responsibility for ecological breakdown: a fair-shares assessment of resource use, 1970–2017. Lancet Planet Health 6, e342–e349. https://doi.org/10.1016/S2542-5196(22)00044-4.

Hille, E., Möbius, P., 2019. Environmental policy, innovation, and productivity growth: controlling the effects of regulation and endogeneity. Environ. Resour. Econ. 73. https://doi.org/10.1007/s10640-018-0300-6.

Jiang, S., Mentel, G., Shahzadi, I., Jebli, M.B., Iqbal, N., 2022. Renewable energy, trade diversification and environmental footprints: evidence for Asia-Pacific economic cooperation (APEC). Renew Energy 187, 874–886. https://doi.org/10.1016/j.renene.2021.12.134.

Johnstone, N., Hascic, I., Poirier, J., Hemar, M., Michel, C., 2012. Environmental policy stringency and technological innovation: evidence from survey data and patent counts. Appl. Econ. 44. https://doi.org/10.1080/00036846.2011.560110.

Khan, Y., Hassan, T., Guiqin, H., Nabi, G., 2023. Analyzing the impact of natural resources and rule of law on sustainable environment: a proposed policy framework for BRICS economies. Res. Policy 86 (Part A), 104070. https://doi.org/10.1016/j.resourpol.2023.104070.

Kongbuamai, N., Bui, Q., Yousaf, H.M.A.U., Liu, Y., 2020. The impact of tourism and natural resources on the ecological footprint: a case study of ASEAN countries. Environ. Sci. Pollut. Res. 27.

Le, T.-H., Le, H.-C., Taghizadeh-Hesary, F., 2020. Does financial inclusion impact CO2 emissions? Evidence from Asia. Financ. Res. Lett. 34, 101451. https://doi.org/10.1016/j.frl.2020.101451.

Liu, X., Yang, J., Bilan, Y., Shahzad, U., 2023. Resources curse hypothesis and COP26 target: mineral and oil resources economies COVID-19 perspective. Res. Policy 83, 103687. https://doi.org/10.1016/j.resourpol.2023.103687.

Machado, J.A.F., Silva, J.M.C.S., 2019. Quantiles via moments. J. Econ. 213, 145–173. https://doi.org/10.1016/j.jeconom.2019.04.00.

Madaleno, M., Ahmed, Z., Doğan, B., Javeed, S., Vasa, L., 2023. The aptness of import-led growth hypothesis for sustainable development in South Asia: do energy utilization and natural resources matter? Res. Policy 86 (Part B), 104262. https://doi.org/10.1016/j.resourpol.2023.104262.

Majeed, A., Wang, L., Zhang, X., Muniba, Kirikkaleli, D., 2021. Modeling the dynamic links among natural resources, economic globalization, disaggregated energy consumption, and environmental quality: fresh evidence from GCC economies. Res. Policy 73. https://doi.org/10.1016/j.resourpol.2021.102204.

Mamghaderi, M., Mamkhezri, J., Khezri, M., 2023. Assessing the environmental efficiency of OECD countries through the lens of ecological footprint indices. J. Environ. Manag. 338, 117796. https://doi.org/10.1016/j.jenvman.2023.117796.

Musah, M., Onifade, S.T., Satrovic, E., Nkyi, J.A., 2024. Assessing the palliative aspects of green innovations in the non-linear tendencies of environmental sustainability-financial globalization nexus among West African states. Geosci. Front. https://doi.org/10.1016/j.gsf.2024.101893, 101893.

Ni, X., et al., 2022. Natural resources volatility, renewable energy, R&D resources and environment: evidence from selected developed countries. Res. Policy 77, 102655. https://doi.org/10.1016/j.resourpol.2022.102655.

OECD, 2008. Eco-Efficiency. OECD Publishing, Paris. https://doi.org/10.1787/9789264040304-en.

OECD, 2009. Natural Resources and Pro-Poor Growth. OECD. https://doi.org/10.1787/9789264060258-en.

OECD, 2015. Material Resources, Productivity and the Environment (OECD Green Growth Studies). OECD. https://doi.org/10.1787/9789264190504-en.

OECD, 2019. Addressing Industrial Air Pollution in Kazakhstan. OECD. https://doi.org/10.1787/0e04ea86-en.

OECD, 2022. Organisation for Economic Co-operation and Development: The OECD Environmental Policy Stringency Index. https://stats.oecd.org/Index.aspx?DataSetCode=EPS (accessed 30.8.23).

OECD, 2023. Organisation for Economic Co-operation and Development: Gross Domestic Spending on R&D (Indicator). https://doi.org/10.1787/d8b068b4-en (accessed 30.8.23).

OECD, 2024. OECD Environmental Performance Reviews: Chile 2024. OECD. https://doi.org/10.1787/5bc65d36-en.

Olawumi, T.O., Chan, D.W.M., 2018. A scientometric review of global research on sustainability and sustainable development. J. Clean. Prod. 183. https://doi.org/10.1016/j.jclepro.2018.02.162.

Onwe, C., Bandyopadhyay, A., Hamid, I., Rej, S., Hossain, M.E., 2023. Environment sustainability through energy transition and globalization in G7 countries: what role does environmental tax play? Renew. Energy 218, 119302. https://doi.org/10.1016/j.renene.2023.119302.

Pesaran, M.H., 2004. General diagnostic tests for cross section dependence in panels. In: Cambridge Working Papers in Economics No. 0435. University of Cambridge, Faculty of Economics.

Pesaran, M.H., 2007. A simple panel unit root test in the presence of cross-section dependence. J. Appl. Econ. 22 (2), 265–312.

Porter, M.E., van der Linde, C., 1995. Toward a new conception of the environment-competitiveness relationship. J. Econ. Perspect. 9 (4), 97–118. https://doi.org/10.1257/jep.9.4.97.

Satrovic, E., Zafar, M.W., Suntraruk, P., 2024a. Achieving ecological sustainability in European Union: the role of fiscal decentralization and green innovation. J. Clean. Prod. 445, 141316. https://doi.org/10.1016/j.jclepro.2024.141316.

Satrovic, E., Gyamfi, B.A., Alola, A.A., Agozie, D.Q., 2024b. Ecological security and agricultural production in the Arab league: is financial development moderating the interaction? J. Environ. Manag. 363, 121376. https://doi.org/10.1016/j.jenvman.2024.121376.

Satrovic, E., Cetindas, A., Akben, I., Damrah, S., 2024c. Do natural resource dependence, economic growth and transport energy consumption accelerate ecological footprint in the most innovative countries? The moderating role of technological innovation. Gondwana Res. 127, 116–130. https://doi.org/10.1016/j.gr.2023.04.008.

Shahid, R., Shahid, H., Shijie, L., Jian, G., 2024. Developing nexus between economic opening-up, environmental regulations, rent of natural resources, green innovation, and environmental upgrading of China - empirical analysis using ARDL bound-testing approach. Innov. Green Dev. 3 (1), 100088. https://doi.org/10.1016/j.igd.2023.100088.

Shi, Y., Li, J., Fang, Z., Li, Y., Hu, H., Nie, W., Meng, F., 2024. Probing the role of natural resources and urbanization towards ecological sustainability in BRICST economies. Res. Policy 91, 104739. https://doi.org/10.1016/j.resourpol.2024.104739.

Sohag, K., Husain, S., Soytas, U., 2024. Environmental policy stringency and ecological footprint linkage: mitigation measures of renewable energy and innovation. Energy Econ. 136, 107721. https://doi.org/10.1016/j.eneco.2024.107721.

Sun, Y., Gao, J., 2023a. Natural resource endowment and its lmpact on ecological efficiency. Res. Policy 87, 104272. https://doi.org/10.1016/j.resourpol.2023.104272.

Sun, Yi, Gao, J., 2023b. Natural resource endowment and its lmpact on ecological efficiency. Res. Policy 87, 104272. https://doi.org/10.1016/j.resourpol.2023.104272.

Sun, H., Edziah, B.K., Kporsu, A.K., Sarkodie, S.A., Taghizadeh-Hesary, F., 2021. Energy efficiency: the role of technological innovation and knowledge spillover. Technol. Forecast. Soc. Chang. 167, 120659. https://doi.org/10.1016/j.techfore.2021.120659.

Ullah, S., Luo, R., Nadeem, M., Cifuentes-Faura, J., 2023a. Advancing sustainable growth and energy transition in the United States through the lens of green energy innovations, natural resources and environmental policy. Res. Policy 85, 103848. https://doi.org/10.1016/j.resourpol.2023.103848.

Ullah, S., Adebayo, T.S., Irfan, M., Abbas, S., 2023b. Environmental quality and energy transition prospects for G-7 economies: the prominence of environment-related ICT innovations, financial and human development. J. Environ. Manag. 342, 118120. https://doi.org/10.1016/j.jenvman.2023.118120.

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. https://doi.org/10.1002/sd.2116.

UNCTAD, 2023. United Nations Conference on Trade and Development.

Villanthenkodath, M.A., Ansari, M.A., Balsalobre-Lorente, D., Satrovic, E., 2024. The comprehensive impact of economic growth on environmental quality: insight established on material, carbon, and ecological footprint. Oper. Res. Forum. 5, 70. https://doi.org/10.1007/s43069-024-00355-3.

Wang, K., Yan, M., Wang, Y., Chang, C.P., 2020. The impact of environmental policy stringency on air quality. Atmos. Environ. 231. https://doi.org/10.1016/j.atmosenv.2020.117522.

Wang, W., Rehman, M.A., Fahad, S., 2022. The dynamic influence of renewable energy, trade openness, and industrialization on the sustainable environment in G-7 economies. Renew. Energy 198, 484–491. https://doi.org/10.1016/j.renene.2022.08.067.

WB, 2023. World Bank: World Development Indicators [WWW Document]. URL. https://datacatalog.worldbank.org/search/dataset/0037712 (accessed 14.7.23).

Westerlund, J., 2005. New simple tests for panel cointegration. Econ. Rev. 24, 297–316. https://doi.org/10.1080/07474930500243019.

Wolde-Rufael, Y., Mulat-Weldemeskel, E., 2021. Do environmental taxes and environmental stringency policies reduce CO2 emissions? Evidence from 7 emerging economies. Environ. Sci. Pollut. Res. 28. https://doi.org/10.1007/s11356-020-11475-8.

Xiaoman, W., Majeed, A., Vasbieva, D.G., et al., 2021. Natural resources abundance, economic globalization, and carbon emissions: Advancing sustainable development agenda. Sustain. Dev. 29, 1037–1048. https://doi.org/10.1002/sd.2192.

Xie, P., Xu, Y., Tan, X., Tan, Q., 2023. How does environmental policy stringency influence green innovation for environmental managements? J. Environ. Manag. 338, 117766. https://doi.org/10.1016/j.jenvman.2023.117766.

Xue, C., Shahbaz, M., Ahmed, Z., Ahmad, M., Sinha, A., 2022. Clean energy consumption, economic growth, and environmental sustainability: what is the role of economic policy uncertainty? Renew. Energy 184, 899–907. https://doi.org/10.1016/j.renene.2021.12.006.

Yadav, M., Aneja, R., Ahmed, W., 2023. Do clean energy transition, environment degradation, and energy efficiency influence health expenditure: empirical evidence from emerging countries. J. Clean. Prod. 428, 139355. https://doi.org/10.1016/j.jclepro.2023.139355.

Yıldız, T.D., 2023. How can shares be increased for indigenous peoples in state rights paid by mining companies? An education incentive through direct contribution to the people. Res. Policy 85, 103948. https://doi.org/10.1016/j.resourpol.2023.103948.

Yıldız, T.D., 2024. Considering the development levels of countries, contributions of mineral recovery from mining tailings and urban mining wastes to sustainability criteria – A review. Res. Policy 99, 105399. https://doi.org/10.1016/j.resourpol.2024.105399.

Yıldız, T.D., Güner, M.O., Kural, O., 2024. Effects of EU-compliant mining waste regulation on Turkish mining sector: a review of characterization, classification, storage, management, recovery of mineral wastes. Res. Policy 90, 104836. https://doi.org/10.1016/j.resourpol.2024.104836.

Yirong, Q., 2022. Does environmental policy stringency reduce CO2 emissions? Evidence from high-polluted economies? J. Clean. Prod. 341. https://doi.org/10.1016/j.jclepro.2022.130648.

Zheng, S., Kahn, M.E., Sun, W., Luo, D., 2014. Incentives for China's urban mayors to mitigate pollution externalities: the role of the central government and public environmentalism. Reg. Sci. Urban Econ. 47. https://doi.org/10.1016/j.regsciurbeco.2013.09.003.

Zou, Y., Wang, M., 2024. Does environmental regulation improve energy transition performance in China? Environ. Impact Assess. Rev. 104 (January 2024), 107335. https://doi.org/10.1016/j.eiar.2023.107335.