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Environmental Quality and Sustainability: Exploring the Role of Environmental Taxes, Environment-Related Technologies, and R&D Expenditure

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Abstract: The surge in economic and human development has led to increasing concerns about environmental degradation, thus necessitating effective strategies to enhance sustainability and environmental quality. Therefore, this study empirically examines the impact of environmental fiscal policies, environmental technologies, and research and development (R&D) expenditures on achieving environmental sustainability in the G7 countries. Using advanced econometric techniques, including the Cross-Sectionally Augmented Autoregressive Distributed Lags (CS-ARDL) model and the Dynamic Common Correlated Effects (DCCE) approach, the study identifies both short-run and long-run correlations between the aforementioned variables and their impact on greenhouse gas (GHG) emissions. Our findings confirm the inverted U-shaped Kuznets Curve relationship and reinforce previous literature on the complex dynamics between economic growth and GHG emissions specific to developed countries. The research also supports the effectiveness of well-designed environmental taxes in reducing environmental degradation and GHG emissions, consistent with and extending existing studies in this area. In addition, the study provides empirical evidence of the critical role of environmental technologies and targeted R&D expenditures in improving environmental quality. In terms of policy implications, our research underscores the urgency for policymakers in the G7 countries to fine-tune environmental taxation mechanisms and increase investment in sustainable technological solutions. Specific recommendations include the development of more efficient tax systems that adhere to the polluter-pays principle, as well as financial incentives such as tax credits and subsidies aimed at accelerating green technology adoption and innovation. In doing so, the study seeks to contribute to the broader discourse on environmental policy and sustainable development, providing valuable perspectives for both the academic community and policy actors.

Keywords: Environmental taxes, environment-related technologies, public environmentally related R&D expenditure, environmental sustainability, G7 countries, CS-ARDL, DCCE.

1. Introduction

In the age of accelerating globalization and industrial growth, the world is coming to terms with an uncomfortable but undeniable truth: climate change is an urgent, far-reaching crisis that poses one of the most serious challenges facing humanity today. Unlike isolated disasters or theoretical future scenarios, climate change is already making its devastating presence felt, altering ecosystems, destabilizing economies, and eroding the social fabric of communities worldwide. This grim reality is exacerbated by our collective drive for rapid economic development, a pursuit often marred by a shortsighted neglect of environmental stewardship. In the race for prosperity, countries are often guilty of overlooking the unsustainable rise in energy consumption and the alarming escalation in CO₂ emissions that are fueling the vicious cycle of global warming. The consequences are not only rising temperatures, but also other profound environmental changes, including worsening extreme weather events, rising sea levels, and the destruction of habitats and biodiversity.

Given the magnitude and complexity of these overlapping crises, the international community has adopted several frameworks for coordinated action. Among the most influential are the Kyoto Protocol of 2005 and the Paris Agreement established at COP21 in 2015. The latter sets an ambitious goal of limiting global temperature increases to well below 2°C, with a further goal of 1.5°C above pre-industrial levels. These global efforts are complemented by the United Nations Sustainable Development Goals (SDGs) and the 2030 Agenda - holistic frameworks that aim to systematically address a range of global challenges, including but not limited to poverty, inequality, climate action, and environmental sustainability. Goals such as transitioning to renewable energy sources (SDG-7), promoting innovation (SDG-9), and taking direct action on climate issues (SDG-13) provide a structured path forward.

Within this matrix of global initiatives, the G7 countries, which include Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States, occupy a unique and critical position. They are disproportionately large emitters of CO₂ and collectively wield significant influence over global economic and political trends. These countries are endowed with unprecedented levels of industrialization and technological sophistication, assets that enable them to act decisively. But herein lies the dichotomy: while these nations have formally committed to frameworks such as the Paris Agreement, assessments such as the United Nations Environment Programme's (UNEP) "Emissions Gap Report 2020" reveal a troubling disconnect between the goals pledged and the concrete actions taken. This means that the G7 has a responsibility not just to follow, but to lead by adopting ambitious environmental policies. These could include progressive environmental taxes, significant public investment in research and development for green technologies, and a rapid transition away from fossil fuels to renewable energy sources.

The path to a sustainable future is complex and full of hurdles. The struggle is multi-dimensional, involving not only environmental challenges, but also economic considerations, political will, and social acceptance. While there is a wealth of research on environmental policy, current research is limited in scope and often examines variables in isolation rather than in an interrelated framework, particularly in the context of the G7 countries. This study aims to fill this critical research gap. Using advanced econometric techniques, such as cross-sectional autoregressive distributive lag (CS-ARDL) and dynamic common correlated effects (DCCE) models, we explore the multifaceted relationships between environmental taxes, public R&D expenditures on environmentally oriented

projects, and the adoption of green technologies. The research situates these variables within the theoretical framework of the Environmental Kuznets Curve, providing a structured understanding of how economic development and environmental degradation can be decoupled through strategic policy interventions.

The contributions of this study are manifold. First, it focuses on the G7 countries, whose decisions and policies have a massive and disproportionate impact on global environmental health. Second, we employ cutting-edge econometric techniques that not only lend credibility to our findings, but also allow for a more textured understanding of the phenomena under study. This is a methodological contribution to the field of environmental economics. Third, our research explores the complex ways in which fiscal policies, technological interventions, and public expenditures interact to influence environmental outcomes. In doing so, we provide a more holistic view of the complex interplay between economic growth and environmental sustainability. Moreover, our findings have broader implications for global sustainability. They align with key objectives of the United Nations Sustainable Development Goals, transforming this research from an academic exercise into an actionable blueprint for societal change. The findings also serve as a cornerstone for policy deliberation and reform, validating and extending the Environmental Kuznets Curve hypothesis. The study even reveals the synergistic effects of environmental taxes, green technologies, and public R&D spending, suggesting an integrated policy approach as a more effective strategy to combat climate change.

The paper is organized as follows: Section 2 provides the theoretical background and a brief literature review. Section 3 outlines the theoretical framework, empirical modeling, and methodology. Section 4 presents and discusses the results of the study, while Section 5 concludes with policy recommendations and avenues for future research.

2. Background and literature review

2.1. Environmental taxation and environmental quality

Environmental taxation has increasingly become an integral component of climate policy debates in various countries, with a particular focus on carbon taxes. At the forefront of these initiatives are the G7 countries, which have embraced these tax regimes to a large extent as a sign of their commitment to climate change mitigation. At the same time, it is worth noting that alternative strategies, such as emissions trading systems (ETS) and cap-and-trade mechanisms, have also gained traction in other jurisdictions. To assess the actual impact and effectiveness of these fiscal measures, the academic community has conducted extensive research, resulting in a wealth of evidence that provides a comprehensive view of their impact on carbon emissions.

To illustrate, Morley (2012) made a seminal contribution using the two-stage GMM technique. Focusing on data from European Union member states and Norway from 1995 to 2006, his study provided empirical evidence that environmental taxes led to significant reductions in CO₂ emissions. This finding became fundamental to subsequent studies advocating the benefits of such fiscal measures. With a broader scope, Hashmi and Alam (2019) ventured into a more comprehensive analysis, covering 29 OECD countries from 1999 to 2014. Their complex examination of the relationship between green patents, environmentally driven innovation,

regulatory frameworks, and CO₂ emissions provided compelling evidence. Their findings reinforced the concept that environmental taxes serve as a linchpin in efforts to reduce CO₂ emissions. Their study alluded to the potential of environmental taxes not only as a deterrent, but also as a catalyst for green innovation and sustainable technological advancement.

Delving deeper into the European landscape, Ghazouani et al. (2021) examined annual data from 1994 to 2018 for nine major European economies. Their findings crystallized the perspective that the introduction and proper structuring of environmental taxes can be a powerful tool to effectively curb pollution outputs. The precision of their data underscores the importance of long-term commitment and proper policy implementation. Meanwhile, in a more recent and comprehensive analysis, Zhang and Zheng (2023) synthesized a variety of determinants that influence carbon emissions. By focusing on factors, such as economic growth trajectories, nuances in global trade patterns, and advances in energy efficiency in the G7 countries from 1990 to 2020, they painted a holistic picture of the environmental landscape. Using the robust CS-ARDL econometric model, their research cemented the positive role of environmental taxes in steering nations toward a path of reduced CO₂ emissions. Examining the differential impacts across different economic landscapes, Chen et al. (2022) offered a nuanced observation. Their research posited that environmental taxes leave a more profound positive imprint on the environmental health of OECD countries compared to their non-OECD counterparts. This distinction highlighted the importance of contextual considerations and the need to tailor fiscal policies based on the economic and developmental status of nations.

On another front, studies have also ventured into sector-specific analyses. For instance, Meireles et al. (2021) examined the transport sector, notorious for its carbon footprint, in 11 Mediterranean European countries. They investigated the impact of transport taxes and vehicle registration taxes on CO₂ emissions in 11 Mediterranean European countries. Their findings indicate that these two fiscal levers exert a pronounced negative pressure on CO₂ emissions, especially in the long run, highlighting the potency of sector-specific interventions. Furthermore, widening the geographical lens, Sarpong et al. (2023) dissected the nexus between environmental taxes, the adoption of renewable energy sources, the diffusion of clean fuel technologies for cooking, urbanization trends, population growth dynamics, and overall environmental degradation in the E7 economies. Their multifaceted analysis shed light on the effectiveness of environmental taxes in curbing environmental degradation, especially when these fiscal measures are synchronized with other sustainable initiatives. Furthermore, the Nordic countries, often lauded for their sustainable efforts, were the focus of He et al. (2019). Using the ARDL model and examining data from 1994 to 2016, their research postulated a notable observation: the Nordic countries exhibited greater reductions in both CO₂ emissions and total energy consumption compared to the G7 countries. This finding provoked introspection about the interplay of cultural, political, and economic factors in influencing environmental policy outcomes. In a similar vein, Hao et al. (2021) employed the CS-ARDL approach to examine data from 1991 to 2017. Their results described the multiple influences of environmental taxes, renewable energy deployment, and human capital development on carbon emissions. An intriguing aspect of their study was the revelation that a robust interconnectedness among these variables is paramount to generate a green growth trajectory and significantly curb carbon emissions. Similarly, Safi et al. (2021) provided a comprehensive perspective by integrating various econometric techniques to analyze data from 1990 to 2019. Their research suggested that environmental taxes, if properly designed and implemented, could

be formidable tools in the arsenal against rising carbon emissions. They also underscored the indelible role of environmental R&D initiatives in amplifying the positive effects of such taxes, paving the way for achieving ambitious carbon neutrality targets.

However, some studies question the direct effectiveness of environmental taxes. Doğan et al. (2022), using the FMOLS technique and survey data from 1994 to 2014, found nuanced results. While their study confirmed the general consensus that environmental taxes tend to reduce carbon emissions, they revealed heterogeneity in these effects across G7 countries. This variability underscores the importance of understanding regional and national idiosyncrasies when designing and implementing environmental tax systems. Moreover, several studies have shed light on the complexity of the terrain, suggesting that not all environmental taxes, especially if not designed wisely, will yield the desired green dividends. King et al. (2019) delved into the intricacies of sector-specific carbon taxes. Using a dynamic general equilibrium model, they articulated concerns about the unintended consequences of such taxes. The potential for a sector-specific carbon tax to inadvertently increase overall emissions due to complicated intersectoral dynamics emerged as a key finding. This calls for a more nuanced understanding of the economic ecosystem when introducing such fiscal measures. From a different perspective, Özmen et al. (2022) embarked on an extensive investigation, analyzing annual data from various countries such as Australia, Chile, Finland, the United Kingdom, and Sweden from 1972 to 2017. Contrary to many prevailing findings, their results called into question the often-assumed positive environmental impact of fiscal policies. None of the countries in their study showed the expected reduction in pollution, leading them to consider the nuanced factors that might be at play in these countries. Similarly, Silajdžić and Mehić (2018) conducted an in-depth examination of the impact of energy and transportation taxes in ten transition economies from 1995 to 2015. Using the FMOLS model, they found that energy taxes had an unexpectedly positive and statistically significant impact on CO₂ emissions, contrary to the desired outcome. This counterintuitive result underscores the need to frequently re-evaluate and fine-tune policies to achieve desired environmental goals. At the same time, Hájek et al. (2019) investigated the effectiveness of carbon taxes in the energy sector of selected EU countries between 2005 and 2015. While their findings confirmed the claim that carbon taxes can indeed reduce GHG emissions, they found no significant impact on energy intensity. This led to calls for more sophisticated carbon tax frameworks that simultaneously address energy consumption patterns and reduce GHG emissions.

Recent studies provide a more nuanced perspective on this trade-off. Aziz et al. (2021) examined the interplay between environmental policy stringency and economic growth. Their study of 21 OECD countries from 1990 to 2014 found that while policy stringency may hinder economic growth in the short run, it contributes positively over the long run. According to their interpretation of the OECD's Environmental Policy Stringency (EPS) index, a short-term economic slowdown gives way to a long-term economic boost once a certain EPS threshold is reached. For policymakers seeking to strike a balance between environment-first initiatives and maintaining economic vitality, such findings offer both a warning and a beacon. On a related spectrum, Ullah et al. (2023) provide a fresh perspective on the intertwined realm of environmental taxes and the elusive goal of environmental sustainability. Examining the top seven green economies, their innovative use of the quantile-on-quantile (QQ) regression method paints a picture of differential impacts across quantiles of environmental sustainability. This non-linear relationship, especially the pronounced impact at the upper-middle quantiles in the majority of countries studied, is both

intriguing and a call to recalibrate expectations. Furthermore, diving into the macrocosm of environmental taxes, Youssef et al. (2023) focus on the European Economic Area (EEA). Their research, a deep dive into the intricate ballet of environmental taxes, productive capacities, and the looming specter of climate change, yields fascinating insights. The interplay of CS-ARDL and Dynamic Common Correlated Effects (DCCE) models in their study reveals the presence of an Environmental Kuznets Curve within the EEA landscape. The revelation that while environmental taxes curb CO₂ emissions, the power of productive capacities to reduce emissions is enlightening. It reinforces the message that productive capacities could be the vanguard in the fight against climate change.

The range of research summarized above underscores the multifaceted potential, complexity, and labyrinthine nature of environmental taxation, especially when viewed through the prism of the G7. However, the performance of these taxes is not one-dimensional. There are several determinants at play, ranging from the architectural precision of the tax, the quantum of taxation, the elasticity of market demand for high carbon footprint products and services, the presence (or lack thereof) of sustainable alternatives, and the ways in which the revenues generated by these environmental taxes are channeled.

The socio-political dimensions cannot be overlooked either. Environmental taxes, like most policies, do not exist in a vacuum. They rub shoulders with vested interests, lobby groups, and segments of the economy that perceive these taxes as adversarial. This multifaceted opposition argues, often vociferously, that certain sectors bear the brunt of these taxes disproportionately, creating inequities.

The distilled essence of these studies and debates beckons a renewed, more incisive focus. As the world grapples with an evolving climate narrative, the G7 nations, with their economic clout and influence, have a central role to play. This calls for an even deeper examination of the structural integrity of environmental taxes, and how they can be shaped to fit the unique socio-economic and environmental fabric of these nations. This, coupled with proactive, informed dialog, could be the key to unlocking the optimal environmental tax paradigm for a sustainable future.

2.2. The role of environment-related technologies and R&D expenditure

In recent years, the imperatives of environmental sustainability have increasingly intersected with advances in the research and development (R&D) of environmentally friendly technologies. This trend has gained particular momentum in the wake of the introduction of environmental taxes. A foundational theoretical framework known as ecological modernization theory has been instrumental in driving this focus. First formulated in the 1980s, the theory posits that solutions to environmental challenges can be developed through technological innovation (Mol and Sonnenfeld, 2000). In essence, it suggests that the development of more efficient, sustainable technologies, such as carbon-neutral energy systems, has the potential to significantly reduce greenhouse gas emissions and decrease dependence on fossil fuels (Wang et al., 2021). In addition, the theory highlights the role of targeted investment in environmental R&D as a means of creating favorable market conditions, thereby catalyzing private sector investment and accelerating the transition to cleaner, renewable energy sources (Kocak and Alnour, 2022).

Against this theoretical backdrop, governments and businesses, particularly in economically advanced regions such as the G7 countries, have increased their commitment to R&D focused on either developing new environmental technologies or improving existing ones. The European Union, for example, has outlined an ambitious plan to allocate 3% of its GDP to R&D activities by 2020, with a strong focus on environmental technologies (European Commission, 2018). Similarly, Japan has outlined a comprehensive strategy to achieve an 80% reduction in carbon emissions by 2050, a goal that relies heavily on its R&D investments in energy-efficient technologies and renewable energy sources (Ministry of Economy, Trade and Industry, 2021). In North America, the Canadian government has demonstrated its commitment through various programs and initiatives to promote renewable energy, clean technology, and energy efficiency (Government of Canada, 2022). Germany, a global leader in renewable energy, has made significant financial commitments to R&D, specifically targeting breakthrough technologies in the solar and wind energy sectors (Bundesministerium für Wirtschaft und Energie, 2022). The United States has also made strides in this direction, with significant R&D spending aimed at developing fuel cell technologies and advanced batteries, with the goal of a cleaner and more sustainable energy landscape (U.S. Department of Energy, 2022).

All of these investments are driven by the overarching goal of promoting sustainable development while mitigating the negative environmental impacts that often accompany economic activities. In support of these initiatives, Ahmed et al. (2022) assert that targeted R&D investments have the potential to significantly reduce the environmental footprint of industrial and economic activities. Therefore, the alignment of policy, theory, and practice in the area of environmental technologies and R&D represents a proactive and coordinated global effort, particularly led by the G7 countries, to address the pressing challenges of environmental sustainability.

While the theoretical understanding of the relationship between environmental technologies, R&D expenditures, and environmental quality has evolved, the empirical evidence remains a matter of considerable debate among researchers. These empirical investigations fall into two main categories or streams of literature.

The first stream of literature overwhelmingly supports a positive relationship between environmental technologies, R&D and environmental well-being. Numerous studies provide evidence that eco-innovation associated with green technologies offers substantial benefits, ranging from improving energy efficiency to decarbonizing the economy and adapting to climate change, although the methodologies and geographical focus may differ (Abbas et al, 2022; Ahmed et al., 2022; Amri et al., 2018; Belaïd and Massié, 2023; Dauda et al., 2021; Godil et al., 2021; Hashmi and Alam, 2019; Hassan et al., 2020; Jiang and Liu, 2023; Khan et al., 2020; Serener et al., 2022; Sharif et al., 2023). In this context, Dauda et al. (2021) applied the Fully Modified Ordinary Least Squares (FMOLS) method to examine the interplay between innovation, trade openness, and CO₂ emissions in a set of African countries over the period 1996-2016. Interestingly, their analysis concluded that technological progress is inversely correlated with CO₂ emissions, providing an African perspective that confirms the positive role of technology in environmental protection. Similarly, Godil et al. (2021) used the Autoregressive Distributed Lag (ARDL) model to assess China's CO₂ emissions between 1990 and 2018. Their work shows that eco-innovation has led to a reduction in emissions, confirming the environmental benefits of technological progress in the context of a large developing country. The study conducted by Amri

et al. (2018) further enriches this discourse by exploring the Tunisian scenario. Using ARDL models with breakpoints and Granger causality tests, the study found that while the direct effect of technological innovation on CO₂ emissions was statistically insignificant, an indirect contribution was observed in the reduction of emissions through reduced energy consumption. This indirect pathway highlights the subtle, yet significant influences of technological innovation on environmental sustainability in a developing country context. Hashmi and Alam (2019) extend this discourse by examining OECD countries from 1990 to 2016 and find that green technologies are indeed able to reduce CO₂ emissions. Hassan et al. (2020), using the Generalized Method of Moments (GMM) for Asia-Pacific countries between 1971 and 2009, also highlight a direct, positive impact of environmental technologies on environmental quality. Extending the lens to the G7 economies, Khan et al. (2020) confirm that environmental technologies significantly reduce CO₂ emissions, reinforcing the global relevance of this positive relationship. In a more recent study, Belaïd and Massié (2023) provide a relevant addition to the literature by examining the impact of energy efficiency on carbon intensity in Saudi Arabia. Using a quantile regression model, they demonstrate the critical role of energy efficiency in mitigating carbon dioxide emissions and emphasize its importance in the decarbonization process. Their results indicate that energy efficiency improvements could significantly contribute to Saudi Arabia's net-zero emissions target by 2060, highlighting the importance of this mechanism for environmental well-being and climate stability. Jiang and Liu (2023) expanded the scope to include both BRICS and G7 countries, applying FMOLS in their regression analyses and positing the indispensability of technological innovation for carbon neutrality goals. They highlighted the G7 countries' ability to balance economic growth and environmental protection, providing a benchmark for other economies.

The impact of R&D expenditures on environmental quality has also been confirmed by several studies. Dogan and Pata (2022), using the Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) estimator, find a direct positive relationship between R&D spending and environmental quality in G7 countries. Their work is complemented by Hailemariam et al. (2022), who extend the data frame to 1980-2020 and include both advanced and emerging economies. They find that investments in R&D for renewable technologies significantly reduce environmental pollutants such as CO₂ and methane. Inglesi-Lotz (2017) took a long-term view by examining data from 1985 to 2012 in G7 countries and found that R&D investments not only promote economic growth, but also reduce pollution through improved energy efficiency. Shahzadi et al. (2022) extended this narrative by analyzing a broad sample of 40 developed and developing countries from 1995 to 2018, confirming the role of R&D in reducing greenhouse gas (GHG) emissions. Similarly, Omri et al. (2022) use Dynamic Ordinary Least Squares (DOLS) to show that in Saudi Arabia, R&D in low-carbon technologies has significantly reduced carbon emissions that affect population health.

The second stream of empirical research adds a nuanced layer to the understanding of the relationship between environmental technologies, R&D expenditures, and environmental quality. While the first stream primarily tends to find a positive correlation, the second set of studies shows that the dynamics are much more complex, subject to various factors, and context-dependent, such as the study by Amin et al. (2023), which used panel data time series analysis to examine the impact of institutional quality and green technology innovation on CO₂ emissions in five South Asian countries from 1995 to 2020. The study found that while green technologies made a dent in CO₂ emissions, the impact was not statistically significant enough to translate into large-scale

reductions. This suggests that other variables, such as institutional quality, may act as moderators, requiring policymakers to look beyond technological advances. Similarly, Erdoğan et al. (2020) conducted a study using the AMG and CCEMG methodologies to evaluate data from G20 countries from 1991 to 2017. They found that while innovations in sectors such as construction did indeed advance technology, they also paradoxically led to an increase in CO₂ emissions. This finding may suggest that sector-specific dynamics may negate the positive environmental impacts of technological innovation, warranting a more cautious and holistic approach to environmental policy. Contrast these findings with those of Du et al. (2019), who used panel data from 71 global economies from 1996 to 2012. They found a strong income-dependent effect: economies with higher income levels experienced significant reductions in CO₂ emissions due to green technology innovations, while economies with lower income levels did not experience significant benefits. Shobande and Ogbeifun (2023) confirmed this conclusion using the Arellano–Bover/Blundell–Bond estimator, looking at 42 developed and developing countries from 1990 to 2016. They found that income levels act as a threshold for the effectiveness of green technologies, underscoring the idea that economic prosperity may be a prerequisite for effective environmental policies. Meanwhile, the study by Mongo et al. (2021) adds a particularly important facet to this discourse, focusing specifically on the European context. Their results using an autoregressive distributed lag (ARDL) model were intriguing; they found that while the long-term effects of environmental innovations were positive, the short-term effects were counterproductive due to a rebound effect. This research highlights the temporal nuances in the relationship between environmental technologies and CO₂ emissions, suggesting the need for longitudinal studies to better inform policy decisions.

The discussion about R&D spending adds another layer of complexity. While R&D is generally considered a catalyst for innovation and problem solving, several studies have shown that increased spending does not always lead to environmental improvements. Awaworyi Churchill et al. (2019) used nonparametric panel data models on G7 countries from 1870 to 2014 and found a time inconsistency: R&D spending had a negative impact on CO₂ emissions for 75% of the period but was not consistently effective. Chen and Lee (2020) studied 96 countries from 1996 to 2018 using spatial econometric models and found that R&D spending can sometimes exacerbate environmental degradation. Market dynamics also play an important role. Yakita and Zhang (2022) showed that in a mixed duopolistic market, privatization of public firms can lead to a decrease in R&D investment, further complicating the picture. This suggests that market structure itself can act as a barrier or an enabler to environmental sustainability, requiring tailored policy interventions for different economic contexts. Finally, studies such as those by Böhringer and Rivers (2021) and Kander et al. (2015) have warned of the potential for rebound effects, where efficiency gains from new technologies are offset by increases in consumption and economic activity. Moreover, the broader conditions in which these technologies and expenditures operate, such as institutional arrangements, regulatory frameworks, and market conditions, can act as either catalysts or barriers, as pointed out in studies such as those by Ni et al. (2022), Amin et al. (2023) and Erdoğan et al. (2020).

Collectively, this second stream of literature underscores the complex set of factors that condition the impact of environmental technologies and R&D expenditures on environmental quality. Far from a monolithic positive impact, these studies show that outcomes are mediated by a variety of variables, including but not limited to income levels, institutional quality, sector-specific

challenges, market dynamics, and temporal factors. Therefore, policies should be multi-dimensional, adaptive, and context-specific to effectively harness the potential of environmental technologies and R&D for sustainable development.

While there is broad consensus on the essential role of environmental taxes, green technologies, and R&D investment in achieving environmental sustainability, our study seeks to add nuance to this understanding, particularly in the context of the G7 countries. As major contributors to global GHG emissions, these countries face an imperative to develop clean technologies and eco-innovations to meet the ambitious goals of the Paris Agreement (OECD, 2020). Using advanced econometric models, we aim to comprehensively analyze how these key elements interact to shape environmental quality. Our research aims to fill critical gaps and integrate the various elements that existing studies have often examined in isolation, thereby providing a more holistic view that can inform targeted and adaptive policies for sustainable development.

3. Data and methodology

3.1. Data specification

This study uses five variables to examine the impact of environmentally related taxes, environment-related technologies, and R&D expenditures on environmental quality. The variables analyzed are greenhouse gas (GHG) emissions per capita, real gross domestic product per capita (GDPC), environment-related technologies measured as inventions per capita (ERT), public environmentally related R&D expenditures (PERD), and environmentally related tax revenue (ERTR). Table 1 provides a detailed description of the variables, including their definitions, units, and data sources. The study focuses on G7 countries, including Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States, with annual data from 1994 to 2019 obtained from the OECD (2023) databases. Statistical analysis shows that the variables are normally distributed and free of outliers.

Table 1. Variables’ definition and descriptive statistics

Variable	Description	Obs.	Mean	Std. Dev.	Min.	Max.	Source
<i>GHG</i>	GHG emissions (tons of CO2 equivalent per capita)	182	2.473	0.401	1.844	3.143	OECD
<i>GDPC</i>	GDP per capita (constant 2010 US\$)	182	10.625	0.131	10.345	11.013	OECD
<i>ERT</i>	Environment-related technologies per capita (inventions per capita)	182	2.932	0.764	1.118	4.411	OECD
<i>PERD</i>	Public environmentally related R&D expenditure (% of total government R&D spending)	182	0.661	0.691	- 1.057	1.584	OECD
<i>ERTR</i>	Environmentally related tax revenue (% of the GDP)	182	0.288	0.500	- 0.844	1.102	OECD

Note: Variables are log-transformed.

According to the data analyzed, the average GHG emissions per capita are 13.62 tons. The United States has the highest GHG emissions, exceeding 25.97 tons per capita in 2000, while France has the lowest, with 6.57 tons per capita in 2019. The average number of environment-related technologies per capita is 24.84. Japan has the highest number of inventions per capita, with a

value of 82.37 in 2011, while Italy has the lowest, with 3.06 in 1995. In Canada, the share of public environmentally related R&D expenditure in total government R&D expenditure is high, at 4.88%. However, the United States has the lowest level of public funding at 0.35%. On average, environment-related tax revenue as a percentage of GDP is 1.49, with Italy having the highest tax share at 3.01% in 1995 and the United States having the lowest at 0.43% in 2019.

3.2. Model structure and empirical strategy

3.2.1. Model structure

The primary objective of this study is to examine the relationship between environment-related taxes, environment-related technologies, and R&D expenditures aimed at improving environmental quality. To anchor our investigation, we use the well-established Environmental Kuznets Curve (EKC) framework originally introduced by Grossman and Krueger (1991). Our model extends the traditional EKC by incorporating insights from recent research, including Abbas et al. (2022), Ahmad and Satrovic (2023), Aydin et al. (2023) and Doğan et al. (2022). The mathematical specification of this extended EKC model is as follows:

$$GHG_{it} = \alpha_{0i} + \alpha_{1i}GDPC_{it} + \alpha_{2i}GDPCS_{it} + \alpha_{3i}ERT_{it} + \alpha_{4i}PERD_{it} + \alpha_{5i}ERTR_{it} + \varepsilon_{it} \quad (1)$$

Here, i , t , and ε_{it} denote countries, time periods, and the error term, respectively. The coefficients α_{0i} , α_{1i} , α_{2i} , α_{3i} , α_{4i} , and α_{5i} capture the constant, GDP per capita, GDP per capita squared, environment-related technologies, environmentally related R&D expenditure, and environment-related tax revenue, respectively. A statistically significant and positive coefficient for $GDPC_{it}$ and a statistically significant and negative coefficient for $GDPCS_{it}$ would validate the EKC hypothesis, which suggests that GHG emissions initially increase with economic growth but eventually decline after a certain inflection point.

3.2.2. Empirical strategy

This study adopts a systematic approach to panel data analysis, recognizing that the traditional models, such as Fixed and Random Effects, Dynamic OLS (DOLS), Fully Modified OLS (FMOLS), Pooled Mean Group (PMG), and Difference GMM, are often inadequate for complex data structures. These limitations in dealing with cross-sectional dependence and heterogeneity are supported by the existing literature, including studies by Bozatli and Akca (2023), Chudik et al. (2017), and Kuo et al. (2022), which also point to biases due to omitted variables and heteroskedasticity.

To address these methodological challenges, the study employs two advanced econometric models: Cross-Sectionally Augmented Auto-Regressive Distributed Lag (CS-ARDL) and Dynamic Common Correlated Effects (DCCE). These methods are not only theoretically robust, but also provide a corrective framework for the issues identified in the traditional models.

The empirical implementation of the study is planned in sequential steps. First, we use the Pesaran (2015) test to assess the presence of CSD in the units under consideration. Next, we use the Pesaran and Yamagata (2008) statistic to test for country-specific heterogeneity. Having established the existence of cross-sectional dependence and heterogeneity, the next step is to assess the unit root

and stationarity properties of the data series using the second-generation tests such as the Cross-Sectionally Augmented Im, Pesaran and Shin (CIPS) and Cross-Sectionally Augmented Dickey–Fuller (CADF). Once these fundamental elements have been confirmed, the Westerlund (2007) test is used to test for long-run relationships between the variables at both the panel and country levels. If such relationships are confirmed, the CS-ARDL model is then applied to estimate the long-run and short-run coefficients, thereby accounting for slope heterogeneity, endogeneity, and CSD issues. The final stage of the empirical strategy involves a robustness check using the DCCE model. This step ensures that the generated results are not only statistically significant, but also empirically validated, thereby strengthening the reliability of the study’s conclusions.

4. Empirical results

4.1. Cross-sectional dependence test

Since this study was based on panel data, there was a high probability of cross-sectional dependency due to the increasing integration among countries and the potential transmission of shocks from one country to another. Therefore, it was expected that there would be correlations between cross-sectional units, and ignoring this could lead to misleading and biased conclusions (Pesaran, 2015). Therefore, the first step in the analysis was to assess the dependence between cross-sectional units across countries. To do this, the CD test for weak CSD developed by Pesaran (2015) was used, which examines the cross-sectional dependence. The formula used for this test is presented in Eq. 2:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^N \rho_{ij} \right) \quad (2)$$

According to the results in Table 2, the null hypothesis of no cross-sectional dependence between countries was rejected in all tests. This finding implies that an adverse event occurring in one sample country could potentially be transmitted to other countries. Therefore, it is essential to consider the potential correlation between cross-sectional units when analyzing panel data to obtain accurate and reliable results.

Table 2. Pesaran CD test for weak cross-sectional dependence

Variables (in log)	CD-Statistic	P-value
GHG emissions per capita (GHG)	23.341	0.000
GDP per capita (GDPC)	23.366	0.000
Squared GDP per capita (GDPCS)	23.365	0.000
Environment-related technologies per capita (ERT)	23.304	0.000
Public environmentally related R&D expenditure (PERD)	22.076	0.000
Environmentally related tax revenue (ERTR)	20.258	0.000

Notes: The CD statistic is normally distributed under the null hypothesis of no cross-sectional dependence.

4.2. Slope homogeneity test

Slope heterogeneity in panel data analysis can be a critical issue that could lead to biased results. To address this challenge, we employ the slope homogeneity test proposed by Pesaran and Yamagata (2008), which is an improved version of Swamy’s (1970) test. This test method

estimates two values, delta ($\tilde{\Delta}$) and adjusted delta ($\tilde{\Delta}_{adj}$), to test the null hypothesis of slope homogeneity for all individuals, against the alternative hypothesis of slope heterogeneity for a nonzero fraction of pairwise slopes. The test is robust in situations where the time dimension (T) exceeds the number of cross-sections (N) and accounts for cross-sectional dependence in panel data, making it more reliable than other slope heterogeneity tests (Sencer Atasoy, 2017).

The Pesaran and Yamagata's (2008) test is formulated in Eqs. (3) and (4), where T denotes the time dimension, N indicates the number of cross-section units, \tilde{S} represents the modified Swamy (1970) test statistic, and k denotes the independent variables.

$$\tilde{\Delta} = \sqrt{N} \left(\frac{N^{-1}\tilde{S} - k}{\sqrt{2k}} \right) \quad (3)$$

$$\tilde{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1}\tilde{S} - k}{\sqrt{\frac{2k(T-k-1)}{T+1}}} \right) \quad (4)$$

The values of $\tilde{\Delta}$ and $\tilde{\Delta}_{adj}$ computed from our analysis (as shown in Table 3) indicate that we can reject the null hypothesis of slope homogeneity in favor of the alternative hypothesis of slope heterogeneity at the 1% level of significance. This suggests that there is significant heterogeneity among the G7 countries with respect to the variables analyzed. Therefore, we need to apply heterogeneous panel techniques that allow the parameters to vary across countries to account for this heterogeneity.

Table 3. Slope homogeneity test (Pesaran and Yamagata, 2008)

Slope homogeneity tests	Δ statistic	p value
$\tilde{\Delta}$ test	11.277	0.000
$\tilde{\Delta}_{adj}$ test	13.192	0.000

Notes: The null hypothesis for slope heterogeneity test is slope coefficients are homogenous.

4.3. Second-generation panel unit-root tests

To address the observed issue of heterogeneity and cross-sectional dependence across panels, this study employs second-generation unit-root tests, specifically the CIPS and CADF panel unit-root tests. The CIPS test is particularly valuable, because it is designed to handle cross-sectionally dependent variables and provides reliable results even in the presence of slope heterogeneity (Pesaran, 2007). The form of the equation for CADF is expressed as:

$$\Delta Z_{it} = \phi_i + \zeta_i Z_{i,t-1} + \sigma_i \bar{Z}_{t-1} + \sum_{j=0}^p \sigma_{ij} \Delta \bar{Z}_{t-1} + \sum_{j=1}^p \lambda_{ij} \Delta Z_{i,t-1} + \varepsilon_{it} \quad (5)$$

where \bar{Z}_{t-1} and $\Delta \bar{Z}_{t-1}$ represent the averages for the lagged and first differences of each cross-section series.

CIPS statistics are obtained from the CADF, as shown in Eq. 6:

$$CIPS = \frac{1}{N} \sum_{i=1}^n CADF_i \quad (6)$$

The results of the CIPS and CADF tests presented in Table 4 indicate that all variables are stationary at first difference, except for environment-related technologies per capita (ERT) and public environmentally related R&D expenditures (PERD). This implies that the CS-ARDL and DCCD estimation techniques can be used for these variables.

Table 4. Results of panel unit-root tests

Variables (in log)	Level		First-difference		Order
	Without trend	With trend	Without trend	With trend	
Cross-sectionally augmented IPS (CIPS)					
GHG	-1.997	-2.833*	-4.883***	-4.816***	I(1)
GDP	-1.772	-2.599	-3.145***	-3.168***	I(1)
GDPCS	-1.763	-2.603	-3.149***	-3.165***	I(1)
ERT	-2.999***	-2.757*	-4.910***	-4.969***	I(0)
PERD	-2.459**	-2.741*	-5.422***	-5.447***	I(0)
ERTR	-1.082	-1.963	-4.032***	-4.275***	I(1)
Cross-sectionally augmented Dicky–Fuller (CADF)					
GHG	-2.107	-2.122	-3.069***	-3.186***	I(1)
GDP	-2.202	-2.337	-2.711***	-2.860***	I(1)
GDPCS	-2.196	-2.332	-2.703***	-2.872***	I(1)
ERT	-2.908***	-2.747*	-3.709***	-3.729***	I(0)
PERD	-2.570**	-2.758*	-3.932***	-4.038***	I(0)
ERTR	-1.556	-2.054	-4.283***	-4.657***	I(1)

Notes: The panel unit-root test was performed under the null hypothesis wherein the variables are homogeneous non-stationary. ***, **, and * denote statistical significance level at 1%, 5%, and 10%, respectively.

4.4. Panel cointegration tests

After confirming that the variables are stationary, the next step is to test for the existence of long-run relationships between the variables, considering heterogeneity and cross-sectional dependence. To this end, the study employs the panel cointegration test of Westerlund (2007), which is based on the following relationship:

$$\Delta y_{it} = \delta'_i d_t + \alpha_i (y_{it-1} - \beta'_i x_{it-1}) + \sum_{j=1}^{p_i} \alpha_{ij} \Delta y_{it-j} + \sum_{j=0}^{p_i} \gamma_{ij} \Delta x_{it-j} + e_{it}$$

The Westerlund (2007) test includes two sets of statistics: the group mean statistics (G_τ and G_α) assess cointegration with one or more components, while the panel statistics (P_τ and P_α) examine cointegration across all cross-sectional components. The test statistics are computed as follows:

$$G_\tau = \frac{1}{N} \sum_{i=1}^N \frac{\hat{\alpha}_i}{SE(\hat{\alpha}_i)} \quad \text{and} \quad P_\tau = \frac{\hat{\alpha}}{SE(\hat{\alpha})} \quad (\text{for large sample})$$

$$G_{\alpha} = \frac{1}{N} \sum_{i=1}^N \frac{T\hat{\alpha}_i}{\hat{\alpha}_i(1)} \text{ and } P_{\alpha} = T\hat{\alpha} \text{ (for small sample)}$$

The results of the Westerlund (2007) tests are presented in Table 5. The tests show that the null hypothesis of no cointegration between the series can be rejected, as indicated by the significant values at the 1% level for both sets of statistics. This result provides strong evidence of a cointegrated parameter measuring the impact of GDPC, ERT, PERD, and ERTR on environmental quality in the G7 countries from 1994 to 2019. With this confirmation, we can proceed to examine the long-run relationship between the variables using the CS-ARDL and DCCE regression estimators.

Table 5. Westerlund's (2007) panel cointegration tests

Statistic	Value	Z-value	P-value
G_{τ}	- 3.335	- 4.201	0.000
G_{α}	- 12.773	- 2.102	0.018
P_{τ}	- 8.183	- 3.585	0.000
P_{α}	- 13.821	- 4.001	0.000

Notes: The G_{τ} and G_{α} statistics assess cointegration for each individual cross-section, while the P_{τ} and P_{α} statistics evaluate panel cointegration when the null hypothesis of no cointegration is assumed.

4.5. CS-ARDL and DCCE regression

In this stage of the analysis, the study carries out the final steps of the empirical strategy outlined earlier, using the CS-ARDL and DCCE methods for robust parameter estimation. The CS-ARDL approach, introduced by Chudik et al. (2016), serves as the first analytical technique to estimate the long-run elasticities of the predefined explanatory variables. This method is designed to deal with a range of econometric complexities, such as CSD, heterogeneity, endogeneity, non-stationarity, and omitted variables in panel data analysis, and is well suited to the specifications presented in the previous sections (Chudik et al., 2017). This model extends the conventional ARDL framework by incorporating the cross-sectional means of the covariates, their lags, and the response variable. This is formalized by transforming Eq. (1) into a CS-ARDL specification appropriate for the dataset under study, expressed as:

$$GHG_{it} = \alpha_0 + \sum_{j=1}^P \beta_{it} GHG_{i,t-j} + \sum_{j=0}^P \alpha_{it} X_{i,t-j} + \sum_{j=0}^3 \phi_{it} \bar{Z}_{i,t-j} + \varepsilon_{it} \quad (7)$$

where GHG_{it} continues to denote environmental quality, and $X_{it} = (GDPC_{it}, GDPCS_{it}, ERT_{it}, PERD_{it}, ERTR_{it})$ consists of the explanatory variables. The coefficients β and ϕ are included to accommodate temporal dynamics, while the term $\bar{Z}_t = (\Delta \overline{GHG}_t, \bar{X}_t)'$ serves to control for cross-sectional dependencies.

The robustness of our results is assessed using the DCCE approach developed by Chudik et Pesaran (2015). The DCCE methodology is explicitly designed to correct for biases and inefficiencies arising from CSD and slope heterogeneity, thus providing a robust alternative to

traditional panel data techniques such as mean group (MG) and pooled mean group (PMG). Specifically, the DCCE model incorporates heterogeneous slopes to assume that a common factor can proxy the variables and allows for both cross-sectional means and lags in the estimation process. Its applicability extends to diverse datasets, whether large or small, balanced or unbalanced, confirming its usefulness (Ditzen, 2021).

The adoption of the CS-ARDL and DCCE methods in this research is not only based on their theoretical robustness but is also supported by empirical evidence in the existing literature. A significant body of recent literature, including studies by Aladejare (2023), Bozatli and Akca (2023), Dahmani et al. (2021a, 2023), Jahanger et al. (2023), Kuo et al. (2022), and Sadiq et al. (2023), has successfully applied these methodologies in analogous research contexts. Such empirical corroboration lends considerable credence to the reliability and validity of the forthcoming results of the study.

4.5.1. Results and discussion

The results from the CS-ARDL panel data estimation of Eq. (7), as summarized in Table 6, provide important insights into the determinants of environmental quality in the G7 countries. The model includes several independent variables: Gross Domestic Product per capita (GDPC), Environmentally Related Technologies (ERT), Environmentally Related Tax Revenues (ERTR), and Public Expenditures on Environmentally Related Research and Development (PERD). An error correction term (ECT) is also incorporated into the model to assess the short-run dynamics and the speed of adjustment to the long-run equilibrium. Indeed, the ECT shows a coefficient of -0.691 with a P-value of 0.001, suggesting that an adjustment of 69.1% is required for the model to converge to equilibrium. This statistically significant result indicates a significant disequilibrium in the environmental quality variables, requiring immediate policy intervention.

Turning to the coefficients for Gross Domestic Product per capita (GDPC, coefficient = 71.830, P-value < 0.001) and its squared term (GDPCS, coefficient = -3.349 , P-value < 0.001), both coefficients are statistically significant at conventional alpha levels, supporting the EKC hypothesis. Specifically, the GDPC coefficient of 71.830 indicates that in the initial stages of economic development, countries tend to prioritize industrial activities that are detrimental to environmental quality. This empirical result corroborates the research of Alola et al. (2023) and Doğan et al. (2022), both of which postulated that the initial stage of industrialization often relies on fossil fuel-intensive and outdated technologies, thereby exacerbating GHG emissions. Conversely, the negative coefficient for GDPCS (-3.349) indicates a reversal of this trend as economies reach higher stages of development, forming an inverted U-shaped curve consistent with the EKC hypothesis. This empirical result is consistent with the existing literature, including Dahmani et al. (2021b), Hao et al. (2021), and Kostakis and Arauzo-Carod (2023), which suggest that maturing economies increasingly adopt renewable energy sources and environmentally efficient technologies, leading to a decline in GHG emissions. The analysis by Amri et al. (2019) adds to this understanding by showing that despite the non-confirmation of the sectoral EKC hypothesis in MENA countries, there is evidence that the service sector emits less CO₂ than the industrial and agricultural sectors, indicating a potential path for these countries to mitigate environmental degradation through economic restructuring. The magnitude of these coefficients is also worth examining. The GDPC coefficient of 71.830 is significant enough to raise concerns about the environmental impact of the early stages of economic development, confirming the “grow-first, clean-up-later” hypothesis. In contrast, the smaller but significant negative coefficient

for GDPCS ($- 3.349$) underscores that economic growth does lead to environmental improvements, albeit at a decelerating rate. This suggests that the relationship between economic development and environmental degradation is not linear, but has a more complex, non-linear pattern. Therefore, a nuanced, multi-pronged policy approach is needed that integrates considerations of sectoral dynamics, as identified by Amri et al. (2019), including a shift toward service-oriented economies, promotion of renewable energy consumption, and improvement of social indicators, such as employment and literacy rates, to promote environmental quality alongside economic growth.

The empirical analysis also sheds light on the role of environment-related tax revenue (ERTR) in improving environmental quality and mitigating GHG emissions, particularly in the context of the G7 countries. The data analysis reveals a diverse but statistically significant negative coefficient for ERTR. In the short run, a unit increase in ERTR is associated with a 0.185 unit reduction in environmental degradation, which is statistically significant at the 10% confidence level. Most importantly, the long-term effects are even more pronounced, showing an average 0.448% reduction in environmental degradation for each unit increase in ERTR, with statistical significance strengthened at the 1% confidence level. These empirical observations are consistent with recent empirical research that underscores the utility of environmental taxation as an effective policy instrument. These empirical observations are consistent with recent research highlighting the effectiveness and complexity of environmental tax policies. For example, Liu et al. (2023) extend the discussion beyond simple carbon pricing mechanisms to focus on the “double dividend” of industry-differentiated carbon taxes. They argue that revenue recycling schemes can mitigate the economic drawbacks of such taxes while enhancing their environmental impact. This is achieved by redistributing tax revenues in ways that are more beneficial to specific industries, such as reducing corporate income taxes or subsidizing clean energy sectors. These findings are supported by other studies, including Ahmad and Satrovic (2023), Ahmed et al. (2022), Hao et al. (2021), Safi et al. (2021), and Shayanmehr et al. (2023), which collectively argue that carefully designed environmental taxes can effectively address issues of environmental degradation, including GHG emissions, while also having the potential to improve economic performance. Nevertheless, the results should be interpreted considering their limitations. The negative coefficient for ERTR, while statistically significant, is only achieved at the 10% level. This calls for a tempered interpretation and a cautious approach to policy extrapolation. This complex empirical landscape can be partially explained by relying on Pearce’s (1991) concept of the “double dividend”. According to this theory, the fiscal instrument of environmental taxation plays two roles: a “green dividend” that discourages polluting activities, and a “blue dividend” that reallocates tax revenues to address other macroeconomic distortions, such as reducing the tax burden on labor (Liu et al., 2023; Shayanmehr et al. 2023). Importantly, the limited statistical significance could also be indicative of lagged policy effects, transitional industrial adjustments, or inadequate policy enforcement. In addition, revenues from these environmental taxes are often channeled into research and development of cleaner technologies, a variable that may take time to manifest itself in empirical data. Therefore, it may be premature to discount the full effectiveness of environmental taxes in shaping more sustainable behavior. Looking at the issue longitudinally, environmental taxation aspires to induce systemic behavioral changes in both individuals and firms (Wolde-Rufael and Mulat-Weldemeskel, 2023). It aims to gradually shift the infrastructure of energy production and consumption to less harmful forms and also to stimulate investment in green technologies, thereby increasing overall energy efficiency and leading to emission reductions (Zhao et al. 2022). Potential limitations in the form of lagged policy effects, transitional industrial

adjustments, and variations in policy enforcement could account for the limited statistical significance. In addition, revenues from environmental taxes are often allocated to research and development of cleaner technologies, a parameter that may have a time lag in its empirical manifestation.

Furthermore, our research, corroborated by the data in Table 6, provides compelling evidence that environment-related technologies (ERT) have a transformative impact on environmental sustainability in the target economies. Our results show that the coefficients for both short- and long-term impacts are -0.085 and -0.264 , respectively, and are statistically significant at the 95% confidence interval. Specifically, the data indicate that a 1% increase in ERT investment is associated with a 0.264% reduction in GHG emissions in the long run, confirming the significant potential of ERT to reduce carbon emissions, although not as effectively as some fiscal policies such as the ERTR. Given these statistically significant results, it is plausible to assume that certain subcategories of ERT, such as energy saving technologies, can contribute significantly to optimizing the efficiency of existing energy resources. Although our study focuses primarily on the potential mitigating effect of ERT on environmental degradation, it is worth noting that the negative correlation between ERT and GHG emissions is consistent with broader research addressing different facets of ERT. These range from energy efficiency and waste management to energy transition and pollution prevention (Ben Youssef et al., 2021; Bozatli and Akca, 2023; Tao et al., 2021; Wang et al., 2023). In light of recent energy price spikes and research on the impact of poorly designed climate policies on energy poverty (Belaïd, 2022), our findings underscore the need for well-designed green investments. As energy price increases may deepen the energy poverty trap and exacerbate inequalities, integrating ERT investments could provide a buffer by increasing energy efficiency, potentially mitigating the negative socio-economic impacts of the green transition. Moreover, Belaïd et al. (2023) note that recent energy crises underscore the need for balanced climate mitigation and energy security policies, which can be supported by green investments. While these investments in ERT can enhance energy security, they also serve to accelerate the pace of the sustainable transition. Our findings are also consistent with empirical studies in various developed countries, adding to the growing body of evidence underscoring the widespread applicability and effectiveness of ERT (Abbas et al., 2022; Ahmed et al., 2022; Jiang and Liu, 2023; Khan et al., 2020; Sharif et al., 2023; Serener et al., 2022). Through these potential mechanisms, the influence of ERT could extend beyond immediate energy savings to broader environmental performance across supply chains (Costantini et al., 2017). Therefore, the cumulative implications of these findings strongly support increased investment in ERT as an important strategy for both sustainable development and mitigation of harmful GHG emissions, with the added benefit of addressing the challenges posed by energy poverty and the transition to a green economy.

Regarding the impact of public environmentally related R&D expenditure (PERD) on GHG emissions, our analysis revealed significant negative coefficients of -0.058 and -0.146 for the short- and long-term effects, respectively. This suggests that such public investments lead to the widespread adoption of energy-efficient and environmentally friendly practices across all sectors, including firms and consumers, ultimately contributing to a substantial reduction in GHG emissions and improved environmental quality. In the immediate term, these public investments are critical to reducing carbon emissions, a key step in mitigating global climate change. This is in line with the findings of Safi et al. (2021), who argue that G7 countries need to prioritize environmental R&D to achieve their carbon neutrality goals. In the longer term, our results suggest

that the benefits of PERD are not limited to environmental protection; they also set the stage for sustainable economic growth. This perspective is supported by Ahmed et al. (2022), who point to the multiple returns to R&D investments, including technological advances and a shift toward renewable energy sources. While our research does not unpack the specific mechanisms through which PERD achieves these positive outcomes, we suggest that such investments are expected to stimulate the identification of energy-efficient alternatives that can be adopted by both firms and consumers. These practices align well with the broader goals of the G7 nations, which aim to achieve carbon neutrality by 2050. Moreover, our study is consistent with the previous findings, including those by Awaworyi Churchill et al. (2019), Hailemariam et al. (2022), Li and Jiang (2020), and Omri et al. (2022), which highlight the long-term fiscal and environmental returns of PERD investments. Significantly, our research supports the existing literature advocating for increased national investments in environmental research and development. Such commitments contribute to immediate and substantial reductions in carbon emissions and provide a foundation for long-term economic sustainability. This demonstrates the essential role that PERD plays in shaping a future that is both economically robust and environmentally responsible, benefiting not only firms but also individual consumers and society at large.

Drawing on our results, we observe a clear differentiation in the effectiveness of different policy instruments in curbing GHG emissions in the long run. Specifically, our results highlight the outsized impact of ERTR compared to ERT and PERD. According to our long-run estimates, a 1% increase in ERTR led to a substantial 0.448% reduction in GHG emissions. This is significantly higher than the 0.264% reduction achieved by ERT and the 0.146% reduction achieved by PERD in the target economies. The data therefore suggest a hierarchy of policy effectiveness, with ERTR at the top, followed by ERT and then PERD. This is not to undermine the importance of either PERD or ERT, but rather to emphasize the need for a nuanced, multi-pronged approach to policy formulation. Among the G7 countries, ERT appears to have the most immediate and strongest long-term impact on environmental sustainability. As such, G7 policymakers might consider recalibrating their environmental strategies by tilting the balance more toward ERT initiatives, without completely sidelining the contributions of ERT and PERD. This could set the stage for achieving ambitious carbon neutrality goals more quickly and sustainably, thereby meeting global climate commitments while ensuring economic viability.

Table 6. CS-ARDL panel data estimation results

	Coefficient	Std. Err.	Z-statistics	P-value
Short-run results				
ECT	- 0.691	0.209	- 3.31	0.001
GDPG	71.830	16.173	4.44	0.000
GDPCS	- 3.349	0.755	- 4.43	0.000
ERT	- 0.085	0.039	- 2.05	0.041
PERD	- 0.058	0.023	- 2.21	0.027
ERTR	- 0.185	0.094	- 1.68	0.093
Long- run results				
GDPG	38.602	10.058	3.84	0.000
GDPCS	- 1.798	0.470	- 3.83	0.000
ERT	- 0.264	0.157	- 2.21	0.027
PERD	- 0.146	0.058	- 2.47	0.013
ERTR	- 0.448	0.219	- 2.98	0.003

CD statistic	- 0.99	0.323
Root MSE	0.02	

Notes: The CD statistic test is standard normally distributed under the null of hypothesis of weak cross-sectional dependence.

4.5.2. Robustness evidence

To further validate the reliability of our findings from the CS-ARDL model, we conducted additional robustness tests using DCCE analysis. As shown in Table 7, the DCCE results provide substantial corroborating evidence to support our initial observations. In particular, GDP per capita emerges as a significant contributor to increased GHG emissions in the G7 economies. This confirms the complex relationship between economic growth and environmental degradation and suggests the urgent need for sustainable growth models in these developed countries. On the other hand, the DCCE analysis demonstrates the effectiveness of environmental policies in reducing GHG emissions. With coefficients of $- 0.547$, $- 0.279$ and $- 0.138$, environmental taxes, environmental technologies, and R&D expenditures, respectively, exert a downward pressure on emissions. The consistency between the CS-ARDL and DCCE results reinforces the validity of our research conclusions. This congruence adds an additional layer of reliability to our study and strengthens the argument for prioritizing these policy instruments as effective mechanisms for reducing GHG emissions in the G7 countries.

Table 7. DCCE panel data long-run estimation results

	Coefficient	Std. Err.	Z-statistics	P-value
Dependent variable (CO2)				
GDP	32.987	28.699	2.79	0.005
GDP	- 1.486	1.344	- 2.74	0.006
ERT	- 0.279	0.142	- 3.26	0.001
PERD	- 0.138	0.060	- 2.22	0.027
ERTR	- 0.547	0.282	- 2.38	0.017
CD Statistic	- 1.21			0.225
Root MSE	0.02			

Notes: The CD statistic test is standard normally distributed under the null of hypothesis of weak cross-sectional dependence.

5. Conclusions and policy recommendations

In a world increasingly characterized by environmental degradation, the nexus between environmental fiscal policies, environmental technology development, public environmental R&D expenditures, and environmental quality remains a critical area of academic and policy discourse, particularly within the G7 nations. The present research seeks to provide an empirical examination of this multifaceted dynamic. Using a longitudinal dataset spanning 1994-2019 and employing advanced panel data analytical methods, this research addresses key questions at the intersection of environment, economics, and policy.

The empirical evidence supports the environmental Kuznets curve hypothesis, revealing an inverted U-shaped relationship between economic growth and GHG emissions in the context of the G7 countries. Moreover, the data suggest that well-calibrated environmental fiscal mechanisms

can significantly mitigate GHG emissions. However, the effectiveness of such fiscal policies depends on adherence to design principles, such as proportionality, transparency, predictability, and cost-effectiveness. Furthermore, it is imperative that these taxes are consistent with the polluter-pays principle, while addressing potential redistributive effects. The study also highlights the critical role of environmental technologies in mitigating environmental stressors. Empirical results indicate a significant negative correlation between incremental environmental taxes and environmental degradation, including measurable reductions in greenhouse gas (GHG) emissions. These technologies not only contribute to environmental conservation, but also facilitate the transition from dependence on fossil fuels to a more sustainable economic model based on renewable resources. Given the critical role of the financial sector in catalyzing environmental technologies, the study suggests that targeted financial incentives are essential to mobilize capital for environmentally beneficial ventures. Specifically, fiscal incentives such as tax credits, subsidies, and preferential loan terms emerge as effective mechanisms for stimulating industrial engagement in the development and adoption of green technologies. In addition, our research suggests that public R&D in environmental technologies should be increased, particularly in areas such as renewable energy and carbon capture. To facilitate the adoption of such technologies, tax policies could be designed to allow households to install green energy systems, such as solar panels, at an affordable cost.

From a policy implementation perspective, the study makes several key recommendations. First, environmental tax mechanisms should move beyond their traditional role as revenue-raising instruments to become robust instruments for behavioral change. This requires the incorporation of multi-dimensional economic models that account for both environmental and social externalities. Second, financial incentives should be used tactically to accelerate the adoption of green technologies, recognizing the propensity of financial sector entities to engage in environmental investment. Third, an expanded public R&D investment strategy is needed that goes beyond government research agencies to include academic institutions and public-private collaborations. At the international level, the G7 has an opportunity to provide normative leadership by promoting or strengthening international agreements that commit to promoting sustainable development and the transition to low-carbon economies. These cooperative initiatives have the potential to set a precedent for global policy, thereby broadening the impact of national policies. Complementing this is the need for public education campaigns to promote sustainable behavior in areas ranging from energy consumption to waste management.

These policies are consistent with the goals of transitioning to green energy (SDG-7) and achieving environmental sustainability (SDG-13) through the innovation channel (SDG-9). Implementing these policies can promote sustainable economic growth while reducing pollution in G7 countries and serve as a model for other countries to follow, contributing to global efforts to mitigate climate change and promote a more sustainable future. By prioritizing sustainability, G7 countries can lead the way in building a green economy, creating new job opportunities, and improving the quality of life for their citizens.

While this study makes a significant contribution to the existing body of knowledge, it is important to note its limitations. Our study assumes linear correlations between the variables of environmental taxation, sustainability technologies, and public R&D investment. Future research could explore non-linear relationships or examine specific subcomponents of these variables, perhaps even extending the scope to non-market approaches in developing countries.

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