

Circular Economy, Green Technologies, and Fiscal Policy: Pathways to Ecological Sustainability and Resource Productivity in OECD Countries

X. Huang¹, F. Ren², and A. Nisar^{3*}

¹Faculty of Humanities and Social Sciences,
Macao Polytechnic University, Macao, CHINA
Email: xueyubingji@163.com

² Krieger School of Arts and Sciences,
Johns Hopkins University, Washington, DC, USA
Email: fren4@jh.edu

³ School of Finance,
Central University of Finance and Economics, Haidian, Beijing, P.R. China
Email: asadnisar@email.cufe.edu.cn

*Corresponding Author

ABSTRACT

Global environmental degradation and resource scarcity are among the most critical challenges of the 21st century. OECD (2020) projects a doubling of material consumption by 2060, with over 90 billion tons of resources currently extracted annually and ecological footprints exceeding 1.75 Earths—indicating we consume resources 75% faster than the planet can regenerate them. The last two decades have witnessed OECD countries generating exponential economic growth and currently account for around 60 percent of the global GDP. This growth, however, has come at an extremely high environmental cost, with natural resources being consumed at an alarming rate—material consumption levels jumped by 70 percent since 2000—so questions are being raised about the commitment of these countries toward sustainable development goals (SDGs). This study looks at the interactions between Circular Economy (CIRC), green-enabling technologies (GET), and government green budgets (GGB) with resource productivity (RP) and ecological footprint (EF) through panel data from 23 OECD countries (2001- 2021). Employing the CS-ARDL model, findings reveal that CIRC and GET robustly enhance RP and reduce EF in both the short and long term. GGB, meanwhile, supports RP in the short term and contributes positively to ecological sustainability across both time horizons. These results are further validated using the CS-ECM approach. The study underscores the need for policymakers to strengthen CIRC frameworks, optimize GGB allocation strategies, and accelerate the deployment of GET to foster sustainable development. By leveraging these interconnected tools, OECD countries can significantly advance their progress toward achieving the SDGs by 2030.

Keywords: Circular economy; Green enabling technologies; Government green budget; Resource productivity; Ecological footprint.

Mathematics Subject Classification: 91B76, 62P20

Journal of Economic Literature (JEL) Classification : Q56, C33

1. INTRODUCTION

Today, the issues like food insecurity, environmental pollution, climate change, and decreasing number of natural resources are shaped as new global priorities that require immediate interventions (Shao & He, 2022). To counter these challenges, Sustainable Development Goals (SDGs) are designed, which emphasize access to climate resilience, affordable renewable energy, conservation of natural resources, and protection of the ecosystems (UNDP, 2021). The Paris Agreement, a treaty that aims to limit climate change, was signed in 2015 by 195 nations. It is widely regarded as a significant attempt to stop climate change through collaboration on reducing greenhouse gas (GHG) emissions and implementing adaptation and resilience approaches. However, total carbon emissions raised by a staggering 60% since the United Nations Framework Convention on Climate Change (IEA, 2022) was established in 1992 through different international and domestic policy approaches, and excessive industrial consumption of natural resources continues to threaten the ecological balance and sustainable development of our planet (UNEP, 2019). These environmental challenges indicate a severe need to shift toward "sustainable" and "clean" production systems based on more efficient resource use and ecological protection. Phasing out fossil fuel subsidies, for example, could reduce carbon emissions by 4% and total GHG emissions by as much as 10% (IPCC, 2022).

OECD countries hold a strong and dominant position in global transition toward ecological sustainability due to their economic prominences, environmental responsibilities, and innovation capacity. These countries collectively wield significant macroeconomic influence, shaping the investment flows, global trade patterns, and technological advancements (Azevedo et al., 2017). As major consumers of resources and generators of waste, OECD would have the disproportionate impact on global environment, and their action plans may reverberate the world (Velenturf & Purnell, 2021). These countries possess advanced technological infrastructure and are at the forefront of developing and implementing the innovative solutions to environmental challenges, including advanced waste management systems, renewable energy technologies, and resource-efficient production processes. Their dedication to fulfilling the Sustainable Development Goals (SDGs) and honoring international environmental agreements reflects a clear acknowledgment of the necessity for joint efforts in tackling climate change and advancing sustainable development (Lamichhane et al., 2021). OECD countries are major player in global economy, and their sustainability transitions can set precedent for the other economies, and sustainable development could be a collection of world's most advanced economies (Lübker et al., 2020). OECD countries implement well-developed and ambitious environmental policy to ensure their commitments toward SDGs. They have pledged to lower greenhouse gas emissions, encourage the adoption of renewable energy, and potentially introduce carbon pricing systems to fund green innovations. Nonetheless, imposing OECD-style regulatory benchmarks through broad trade or aid-related penalties has proven to be both counterproductive and ineffective (Shang et al., 2024). Investment in renewable energy, modern energy infrastructure, low-carbon technologies, and digital innovation is an important aspect of improving both RP and EF. Strengthening RP and EF helps OECD countries develop resource governance systems that are less damaging to the environment.

The need to respond to increasing ecological and resource-related pressures has led to a growing number of countries adopting the green economy model (Lu et al., 2022), which seeks to bring together economic growth, productive use of resources, and ecological sustainability, while providing enhanced resilience to climate and global uncertainties (Song et al., 2022). Enhancing RP is one of several approaches to addressing both environmental and economic problems, restoring ecological health (Najam & Malik, 2021), and strengthening the foundation for economic sustainability (Goodwin et al., 2022). Emerged as a cornerstone of sustainable growth, RP is remained a critical focus of the

policymakers and academicians in a pressure to achieve the SDGs (Goodwin et al., 2022; Pan & et al., 2022). Multiple macro-level factors have been recognized as critical to influence RP, such as sustainable industrial development (Rehman et al., 2021), investments in green initiatives (David & Venkatachalam, 2018), reliance on non-renewable energy sources (Awodumi & Adewuyi, 2020) renewable energy transition (Yao et al., 2019), international green trade (Belloumi & Alshehry, 2020) and forestry and agriculture finance (Koenker & Bassett Jr, 1978). Given ongoing environmental and economic challenges, countries need to develop mechanisms that promote ecological sustainability and effective resource usage. In response to this need, the study explores the relationship between CIRC, GET, and GGB on RP and EF levels within the context of OECD countries.

The CIRC concept represents the shift from traditional linear “teak-make-dispose” model to a restorative system whereby waste can be minimized and resource utilization can be maximized at optimal level (Stahel, 2019). Velenturf and Purnell (2021), clarify that a shift brought by CIRC develops the foundational relevance of a change in production and consumption patterns that then leads to resource efficiency, durable products and the creation of closed-loop-systems. At the macro level, countries are taking initiatives to set the targets of waste reduction, advocating for eco-design, and providing incentives of the circular business models to have shared processes (Panchal et al., 2021). These initiatives are intended to make manufacturers responsible for the end-of-life management of products to bring the waste down to the lowest life and assuredly eliminated. Industrial symbiosis, where waste from one industry moves as a resource for another industry, is the gaining attention as a source of optimizing resource use and reducing environmental effects. Additionally, CIRC enables significant opportunity for extending the RP, reducing the waste, and creating new economic opportunities. By employing CIRC principles governments can be able to foster innovation, create new markets, and generate the economic opportunities in recycling, waste management, and remanufacturing areas. CIRC (CIRC) when integrated within the global economy, emerges as an essential tool for sustainable human life on Earth planet (Alves et al., 2024). By promoting reuse, repair, recycle, and refurbishment of materials, it serves as an alternative to reduce the impact of various industries; however, this requires a systematic change in business models, supply chains, and product design to achieve target goals (Silva et al., 2024). So, CIRC could be essential to extend the lifecycle of resources from one side, and on the other side it may support the sustainable development by embracing resource scarcity as a critical challenge of current world (Mateus et al., 2023).

GET are pivotal to drive ecological sustainability by offering the innovative solutions that can mitigate the environmental impacts and enhance resource efficiency across various industries (M. Guo et al., 2020). These technologies span a broad spectrum, encompass renewable energy systems, energy efficient infrastructure, precision agriculture, and advanced waste management processes (Behera & Sethi, 2022). Digital technologies such as the Internet of Things (IoT), big data analytics, and blockchain play a pivotal role in enhancing resource efficiency and facilitating environmental surveillance (Upadhyay et al., 2021). For example, smart grid systems help streamline energy distribution, minimize transmission losses, and enable more effective integration of renewable energy into the power supply network. Precision agriculture, enabled by sensors, drones, and data analytics, facilitates farmers to have optimized irrigation, fertilization, and pesticide application, reduced water consumption, and thus minimize environmental pollution (Arora, 2005; Behera et al., 2023). Advanced waste management systems, incorporating the technologies such as automated sorting and waste-to-energy conversion, can significantly minimize the landfill waste and recover the valuable resources. Moreover, R. Guo et al. (2020) highlight that green-enabling technologies play a significant role in advancing the shift toward a low-carbon economy by offering alternatives to fossil fuels and enhancing energy efficiency. Such technological innovations are vital for achieving global Sustainable Development Goals (SDGs),

including the development of smart and sustainable cities. Therefore, technological innovation could be essential to sustainable manufacturing of the products and services, and thus we could have transition toward a green economy (Ikram, 2022).

GGB can be referred as the government's fiscal approach to align its expenditures with the environmental and economic challenges, thereby it may support the ecological sustainability and resource efficiency (Stahel, 2019). This fiscal approach of involves integrating of the environmental challenges into national and regional level budgeting processes so public funding could be accurately allocated to promote green initiatives and to achieve the SDGs (B. Behera, P. Behera, & N. Sethi, 2024; Green, 2021). On a national scale, governments are now more aware of the significance of integrating sustainability into budgeting processes by dedicating resources to green public investments that back renewable energy, energy efficiency, and pollution management initiatives (Lübker et al., 2020). In this area, environmental tax reform could potentially serve as a major mechanism to spur sustainable behavior while also raising money to reinvest in green initiatives and create a virtuous cycle of fiscal responsibility and environmental sustainability in the country (Li et al., 2020). Green budgeting frameworks enable a structured approach to enable the governments for evaluating the environmental effects of budgetary policies and to make more informed decisions about the resource allocations (von Thiele Schwarz et al., 2016). National governments may deploy carbon pricing mechanism that can impose carbon pricing, and thus encourage the industries, businesses, and individuals to adopt green practices and cleaner technologies (Stahel, 2016). Aligning national budgets with SDGs could be a paramount that requires a comprehensive review of budgetary allocations for ensuring that budgets make direct and significant contributions toward the achievement of environment-related goals such as mitigate greenhouse gas emissions, improve waster quality, and protect biodiversity (Garrone & Grilli, 2010; Petrović & Lobanov, 2020). Additionally, governments with green budget allocations could support the development of macro level fiscal policies where sustainability is prioritized, and environmental factors are integrated into the economic planning and decision-making at national and regional level. Therefore, it can be argued that the adoption of green budgeting strategies enables governments to harness their fiscal capabilities to promote sustainable development and cultivate a more resilient and environmentally responsible economy.

Despite the individual assessments in CIRC implementation, green enabling technology adoption, and green public budgeting, still there is a significant research gap exists at macro-level to present an integrated impact of these three factors on RP and EF, especially in case of largest resource consumer bloc, OECD. (Garrone & Grilli, 2010; Hekkert et al., 2007; Hysa et al., 2020; Yang et al., 2022). Previous studies mainly examine micro-level case studies or sectoral analysis, and they lack in to adopt holistic, cross-national and broader perspective that can capture the complex interactions between these variables at a broader economic. Many studies on CIRC focus on specifical industries or waste management practices, failing to address the systemic changes needed for a transition to a CIRC at the national level (Hysa et al., 2020; Velenturf & Purnell, 2021). Similarly, research on green enabling technologies and GGB often overlooks a broader economic and policy context in which these technologies could be deployed, and thus neglecting the role of government incentives and regulatory framework to promote the adoption (Caglar & Ulug, 2022). The originality of this study lies in the analytical framework that integrates CIRC principles, GET, and green budgeting (GGB), meaning that a holistic picture can be gained about the three continuing impact of these variables on RP and footprint (EF). This study starts to address a significant gap in the literature, and importantly, it makes a number of contributions. First, it is one of the first to study the asymmetric impact of CIRC, GET, and GGB on RP and EF for OECD countries with panel data from 2001 to 2021. Second, second-generation unit root tests are employed for rigorously testing the stationarity of core variables CIRC, GET, GGB, RP

and sustainable ecology to ensure added econometric reliability. Third, the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model is adopted to identify both short-term and long-term asymmetries to provide a more in-depth insight to the dynamic association with the three variables of interest. Lastly, the study provides recommendations for policy makers and other stakeholders who want to reconcile fiscal and ecological activities with Sustainable Development Goals (SDGs).

Following Introduction, Section (2) discusses the literature review, Section (3) covers the methodology, variables, and data of study, Section (4) presents the empirical analysis and discussion of findings, and Section (5) concludes the paper and present policy implications and further research directions.

2. Literature Review

The growing demand for resources across OECD countries underscores the urgent need for more effective resource management strategies to support the achievement of Sustainable Development Goals (SDGs), especially in nations aiming to foster RP and mitigate EF. In context of the OECD countries, the average per capita material consumption increased from 15 to 20 metric tons over the period of 2001-2022, highlighting the scale of consumption (Eurostat, 2023). This surge does not intensify pressure on natural systems only but it also amplifies environmental concerns, especially regarding the pollution and waste disposal. According to a UNEP (2019) report, inefficiencies in resource consumption are closely associated with economic losses, estimated at approximately 2% of global GDP. Moreover, OECD countries are responsible for generating more than 30% of the world's total waste, thereby playing a substantial role in reducing the carbon emissions (Schaffartzik et al., 2014). In this manner, rather than being considered a regional challenge, improving resource efficiency has become a global imperative requiring cooperation and the use of innovative solutions (Jackson & Webster, 2016). Although there have been major technological advancements over the past two decades, the gap between resource consumption and productivity has remained and even widened. The gap is prompting policy attention and action (Schandl et al., 2018). Despite the contributions of technology to productivity improvements, the benefits have eroded as resource use has continued to increase from economic growth and rising consumer demand. The extensive use of the resources by OECD countries questioned about their concerns toward long-term environmental and economic sustainability. As per now OECD countries represent 18% of the world population, and they are account for 40% of the global material extraction, and thus being among the largest carbon emitter bloc across the world (Saidi & Omri, 2020). Additionally, the EF in many OECD countries significantly suppresses their biocapacity, resulting in widespread ecological deficits (Wiedmann et al., 2015). This prevailing growth model in these economies, mainly relying on excessive resource consumption, intensifies the ecological degradation and compounds the global environmental challenges (Hair et al., 2010; Steinberger et al., 2010). Addressing this unsustainable trajectory has become essential to achieve sustainability goals, particularly through the adoption of CIRC principles, green enabling technologies, and government green fiscal actions.

To achieve national and international sustainability targets, the CIRC represents a transformative response to resource inefficiency and negative environmental impacts. Globally, the level of extracted

materials doubled between 1980 and 2010 as it has touched to 72 gigatonnes, and likely to reach at 100 gigatonnes by year 2030 (OECD, 2020). CIRC strategies, especially those related to recycling and material reuse, are useful for applications focused on sustainable waste management. Tisserant et al., 2017 explain that Mexico and Brazil are among those countries, those may particularly benefit from the modern circular economy models (Tisserant et al., 2017). At its core, CIRC promotes a regenerative model that minimizes resource inputs and waste, emissions, and energy leakage through slowing, closing, and narrowing resource and energy loops (Alves et al., 2024). This transition to a circular model is facilitated through durable design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling; thereby linking economic growth with resource consumption and environmental degradation (Corvellec et al., 2022). CIRC paradigm emphasizes on designing products so that when they have been reached to end of their lives, they can be used as raw materials for producing new items, which results in reduced EF and resource consumption (Saidi & Omri, 2020). The primary mechanism of the CIRC includes three principal elements: the provision of materials, the assimilation of waste, and the production of value, underscoring the continual use of resources throughout the production, distribution, and non-consumption stages of commercial activity (Nikolaou et al., 2021). CIRC also supports new types of production and advanced solution technologies that can deliver sustainability while still meeting consumers' demand — thereby achieving economic growth without compromising environmental quality or depleting significant deposits of natural resources (Ho et al., 2024). So, CIRC is focused to redesign production and consumption patterns to ensure the avoidance of environmental impacts and keep natural resources in technosphere for as long as feasible, which can aid society's transition to a new economy (Silva et al., 2019).

The implementation of CIRC principles has great potential to improve resource productivity and improve environmental sustainability at both national and regional scales. By prioritizing waste reduction, material reuse, and product life extension, CIRC approaches allow for greater efficiency of natural resource use, less reliance on primary materials, and a reduction in environmental harm associated with production and consumption (Upadhyay et al., 2021). The CIRC concept promotes the implementation of circular systems that convert output from one productive system into a valuable resource for another productive process thereby, reducing waste and improving efficiency (Silva et al., 2023). Moreover, this model when practiced protects biodiversity, reduces greenhouse gas emissions and encourages industries to transition to sustainable production and consumption patterns (Upadhyay et al., 2021). National policies like the European Union's Circular Economy Action Plan have further supported this transition by creating eco-design regulations, establishing extended producer responsibility systems, and providing financial support for circular economies (Šírová & Zbránková, 2024). These frameworks aim to enable such environment for sustainable business models where regulations can be tailored to industry-specific needs, and CIRC adoption promises some other significant macroeconomic benefits including job creation in recycling and repair sectors, reduced resilience on imported raw materials, and improved resource efficiency. Based on this discussion, it can be argued that CIRC initiatives align closely with the objectives of the Paris Agreement by enabling countries to enhance both RP and reduce EF concurrently. However, despite the recognized advantages of CE practices, there remains a notable gap in the existing literature regarding their specific

environmental and resource efficiency impacts within the context of OECD countries. This study will fill this gap by explaining the economic and environmental potential of CIRC to influence RP and EF in OECD context of OECD countries.

GET encompasses a wide range of sustainability-supporting technologies such as green information and community technology, smart infrastructure, clean energy systems, and automation. These all play a pivotal role to foster resource efficiency, enhance productivity, and facilitate the transition toward carbon neutrality, all of which are linked to SDGs and broader macro-level policies (Ahmed & Elfaki, 2024). These technologies are found instrumental to decouple economic growth from environmental degradation, and thus enabling industries where resources utilization can be optimized, waste generation and carbon emissions can be minimized (Sahoo et al., 2023; Sethi et al., 2024)). As stated by Shukla et al. (2025), green technologies can be implemented within multiple sectors and may help aid the development of a management framework and regulatory frameworks to align economic activities with environmental needs. This integration encourages producers to internalize the environmental and/or resources costs of their economic activity, driving them to improve their innovation towards ecological sustainability and environmental protection (Ikram, 2022). Additionally, utilizing renewable technologies as well as creating renewable technologies, along with the development of appropriate supporting policies and instruments, is an important aspect of the CIRC. Furthermore, the development of advanced technologies such as blockchain in a variety of methods can bolster these efforts and support approaches to cleaner production systems in ways that could contribute significantly to advancing the agenda of the green economy (Ma et al. 2022). Despite the growing recognition of importance of green technologies, research on various types of green technologies and their applications remain limited, indicating a strong need to further explore their benefits to shape green and sustainable economy (Trapp & Kanbach, 2021).

The existing literature often examined the impact of individual technologies in isolation, failing to capture the synergistic effects of combining multiple GETs with CIRC and green fiscal policies to present their sustainable benefits (Lv et al., 2021). There is need of a comprehensive approach to evaluate the effectiveness of GETs that requires the development of integrated framework that considers the interplay between technology innovation, policy intervention, and economic incentives, and thus requires a deeper understanding of barriers and enablers that influence the adoption and diffusion of GETs across various sectors and regions (P. Behera, B. Behera, N. Sethi, et al., 2024; Yang et al., 2024). Undoubtedly, the business agenda of cleaner production, sustainability, and social responsibility underpins the CIRC model; however, potential of technologies like blockchain and artificial intelligence to create cleaner economic transaction processes and promote harmony between environment, economy, and society have been increasingly recognized (Wang & Ren, 2022). Moreover, digital innovations are expected to play a crucial role to enable and trigger green business models, necessitating the change to business models for ensuring that technology is being used effectively (Liu et al., 2020). Previous studies have largely concentrated on the environmental advantages and limitations of GET, with a particular emphasis on OECD countries. To address this gap, the present study explores the dual benefits of GET—specifically its potential to enhance both ecological sustainability and resource efficiency within the OECD context.

GGB, defined as national-level fiscal tools that align budgets with environmental goals, include green taxation, climate expenditure tagging, and carbon fiscal planning, is emerged as the essential instrument for shaping ecological outcomes and promote effective resource governance at macro level. These tools enable governments to incentivize environmentally friendly practices, discourage pollution, and invest in sustainable infrastructure and technologies, thus foster a transition towards a low-carbon and resource-efficiency economy (P. Behera, B. Behera, & N. Sethi, 2024; Caglar & Ulug, 2022). Recent global trends in green budgeting across OECD countries, such as France, Sweden, and Korea, reflect a growing commitment to integrate environmental considerations into the fiscal policy frameworks. Implementing green budgeting practices involves systematically assessment of environmental effects of budgetary decisions, identifying the opportunities for green investments, and tracking the progress toward environmental targets, thereby enhancing the transparency and accountability of government spending in relation to environmental goals (B. Behera, P. Behera, S. Sucharita, et al., 2024; Petrie & Petrie, 2021). Countries, by integrating the sustainability into economic actions, can create new opportunities for sustainable business models, and support sustainable business practices. Government fiscal interventions can play a vital role in advancing the digital economy, which in turn enhances resource allocation efficiency and reduces carbon emissions resulting from inefficient production processes. Additionally, by integrating digital advancements with the real economy, such fiscal support stimulates green innovation and serves as a critical tool in addressing pressing environmental challenges (Jiang et al., 2023).

Previous studies show that there are numerous crucial elements to evaluate the real impact and foster green innovation (Zavagno, 2021). Despite growing adoption of green budgeting practices, challenge remain to ensure the effectiveness to implement and measure the environmental and economic effects. There is need to investigate how green budgeting could be effective to present the potential benefits toward green economy concept through fostering the RP and minimizing the carbon emissions (von Thiele Schwarz et al., 2016). It is reported that carbon pricing significantly fosters the environment where industries and regional governments become accountable to the carbon neutrality goals (Chapman, 2014). In pursuit of green economy, and to achieve the ecological sustainability, government green budgeting can foster the concept of green public infrastructure where people could be directly involved in the process of building green economy. There can be sustainable supply chains, logistic networks, and transportation systems that may use the GGB for being able to ensure their alignment to the carbon neutrality goals, and these all are expected to use CIRC principles may also result from additive manufacturing, which promotes more localized production, waste reduction, and resource efficiency (Rawat & ., 2020). There exists an urgent need to evaluate the extent that government driven green budgeting could influence RP and EF in context of OECD countries.

In summary, this study highlights significant areas of research in the intersection of RP and EF with broader sustainability efforts in OECD countries. The increase consumption of the natural resources across OECD countries for industrial processes emphasizes the urgency to develop sound management techniques to address SDG targets, in particular the RP targets and reductions in carbon emissions. OECD countries with only 18% of the world's population, are currently consuming around 40% of the natural resources of the world (Krausmann et al., 2009), that raises a serious concern about

their current role to achieve SDGs by 2030 (UNEP, 2019). In response to these challenges, the aforementioned three frameworks have developed: CIRC, GET, and GGB. CIRC addresses the concept of sustainable consumption and recycling as an aspect of cleaner production, potential for improvement in RP and job opportunities has also surfaced (Ellen MacArthur, 2015). In contrast, GET builds on the notion of innovation to initiate new technologies by building the digital infrastructure for green innovation and in support of transitioning to low-carbon (Friends of the Earth, 2014). Similarly, Government green budgeting allows the government to have the financial incentives for the regional governments and industries to adopt green and sustainable behaviors (Garrone & Grilli, 2010). This is the first study to put all three major drivers within a single framework to investigate their effects for RP and EF in OECD countries.

3. Theoretical framework, Data and Methodology

3.1. Theoretical framework

This study grounds ecological modernization theory, public finance theory, and innovation system theory to elucidate how OECD countries can strategically leverage CIRC initiatives, green enabling technologies, and GGB to RP and EF (Hysa et al., 2020). The nexus of CIRC with RP and EF can be explained through the lenses of Ecological Modernization Theory (EMT), which posits that economic growth and environmental protection are not mutually exclusive but they can be achieved through systematic innovations and institutional reforms (Mol & Sonnenfeld, 2000). CIRC practices such as recycling, waste-resource loops, eco-design, and industrial symbiosis, reflect EMT's emphasis on environmental integration into the core economic processes (Andersen, 2007). These practices of CIRC enable an environment where there can be reduction in extraction of virgin materials and promotion of resource efficiency, thereby enhancing the environmental performance while supporting the industrialization in a country (Jänicke, 2008). In advanced countries, CIRC initiatives are found as the successful efforts to decrease the EFs by closing the material loops and reducing the waste streams as well (Korhonen et al., 2018). Moreover, EMT's concept aligns with the institutional actors' proposition which states that firms and governments can internalize ecological responsibility through new practices, norms, and technologies (Spaargaren & Mol, 1992). This theoretical framing could be meaningful in the OECD context, where CIRC is promoted not as a waste management strategy but as a systemic shift toward the decoupling of economic activity from environmental harm (Geng et al., 2012).

To further explain the role of green enabling technologies in this nexus, innovation system theory (IST) offers a complementary macro-theoretical perspective by emphasizing the view that development, diffusion, and application of technologies are shaped by the systemic interaction among institutions, firms, knowledge bodies, and policy frameworks (Lundvall, 1992). GET such as AI-enabled waste tracking, blockchain for material traceability, and smart resource management systems directly contribute to the increased RP through enhancing transparency, process efficiency, and monitoring capabilities (Zhou et al., 2020). These technologies serve as the systemic instruments that directly reduce the transaction costs and environmental externalities (P. Behera, L. Sethi, et al., 2024; Hekkert et al., 2007). Moreover, the technological innovations contribute to what Schumpeter termed "creative destruction," arguing that sustainable solutions could replace outdated and resource-intensive models (Markard & Truffer, 2008). The innovation systems can foster the adaptive capabilities and reflectivity,

both could be critical to accelerate the transitions to sustainability (Weber & Rohrer, 2012). In context of OECD countries, GET can facilitate closed-loop production systems, optimize supply chain inputs, and create new service-based business models that can reduce material throughput (Lacy & Rutqvist, 2015). The integration of green technologies thus can strengthen the CE framework by fostering its effectiveness and operational efficiency, and validating the IST claim that institutional and technological complementarities are essential for systemic environmental innovations.

From governance and fiscal policy perspective, institutional theory explains the nexus of how government green budgeting could act as a catalyst for both circular and technological transition of OECD countries. This theory posits that behavior of organizations and systems is directly influenced by the regulatory, normative, and cognitive structures in which they are embedded (Scott, 2008). Green budgeting – defined as the systematic integration of environmental consideration into public finance decisions – reflects institutional commitment to sustainability and frames market behavior through fiscal incentives and disincentives (OECD, 2021). These budgetary mechanisms fund the eco-innovation, waste reduction programs, and green infrastructure, and thus effectively lower the entry barriers and risks linked with the sustainable investments (Bertelli, 2019). Miedzinski et al. (2022) found that public financial support can positively influence the private sector engagement to deploy resource-efficient structure in their processes. Furthermore, green fiscal policies contribute to environmental legitimacy, and reinforce stakeholder expectations for ecological accountability (DiMaggio & Powell, 1983). As governments engage in allocation the resources toward sustainability goals, they also restructure institutional reforms to create the feedback loops that can consolidate ecological values in both policy and practical world (North, 1990). When integrated within CE strategies and technological innovations, green budget may not only enable but also accelerate the progress toward RP and reduced carbon emissions (UNDP, 2021). Therefore, institutional theory offers a foundational understanding of how fiscal and policy instruments serve as levers for embedding sustainability into the economic system.

3.2. Data

This study introduces these models:

Resource productivity = (Circular economy, Green-Enabling Technologies, Government Green budgets, control variables); and

Ecological footprint = (Circular economy, Green-Enabling Technologies, Government Green budgets, control variables).

We can express this model in econometric terms as:

$$RP_{it} = \psi_0 + \psi_1 CIRC_{it} + \psi_2 GET_{it} + \psi_3 GGB_{it} + \psi_4 X_{it} + \vartheta_{it} \quad (1)$$

$$EF_{it} = \psi_0 + \psi_1 CIRC_{it} + \psi_2 GET_{it} + \psi_3 GGB_{it} + \psi_4 X_{it} + \vartheta_{it} \quad (2)$$

where RP_{it} is resource productivity, EF_{it} represents ecological footprint, $CIRC_{it}$ denotes the circular economy, GET_{it} is the green-enabling technologies GGB_{it} represents the government green budgets, X_{it} denotes the control variables, ψ_1 to ψ_4 represent coefficients, ϑ_{it} denotes error term. The present study looks at the association between RP and EF in the context of CIRC practices, GET, and GGB in case of 23 OECD countries. The sample countries have been selected based on the availability of data for all variables of study. The selected 23 OECD countries were: Australia, Portugal, Finland, Italy,

United Kingdom, Japan, Denmark, Switzerland, Germany, Netherlands, Sweden, Canada, Austria, Hungary, Poland, France, Slovenia, Ireland, Republic of Korea, Spain, Turkey, Belgium, and United States. In Table 1 we show the key variables that we used in this study along with an explanation of how we measured each variable, their symbol, their type, and source of data. We select the control variables by following the work of Demirel & Kesidou (2019) and Krausmann et al. (2009).

Table 1: The variables of study and sources

Var. Type	Name of Variable		Symbol	Measure	Source
Dep.	Ecological Footprint		EF	Ecological Footprint (per capita)	Global Footprint Network (2023) International Resource Panel, WDI World Bank
	Resource Productivity		RP	GDP (constant 2015 US\$) / Total material consumption	
Ind.	Circular economy		CIRC	Total Municipal waste generated by each country in million tons/year	OECD (2024)
	Green-enabling Technologies		GET	No. of Enabling technologies (technologies with potential or indirect contribution to GHG emission mitigation).	OECD (2024)
	Government Budgets	Green	GGB	Renewables RD&D per million units of GDP	IEA (2024)
Control	Gross Domestic Product		GDP	GDP per capita (current US\$)	WDI World Bank
	Industrialization		IND	Total Manufacturing value added percentage of GDP	WDI World Bank
	Research and Development Expenditures		RD	R&D expenditures (% of GDP)	WDI World Bank

3.3. Econometric methodology

Recent literature provides a variety of advanced statistical methods built to deal with the complexities of the analysis of panel data. Therefore, the present study employs an advanced panel data approach to assess the impacts of CIRC practices, GET, and GGB on RP and EF. The analysis is based on annual data from a panel of the selected OECD countries from 2001 to 2022. To capture dynamic and structural relationships among the variables, this study employs the Cross-Sectional Augmented Autoregressive Distributed Lag (CS-ARDL) approach, which facilitates in estimating the short-term and long-term casual linkages between variables. This econometric approach is appropriate for macro-panel datasets and it has become a cornerstone in empirical analysis, and thus offer robust capabilities for hypothesis testing, structural modelling and economic forecasting. The Autoregressive Distributed Lag (ARDL) model is a flexible and widely applied in macro-level economic research for time series analysis as it accommodates explanatory variables that are integrated at different levels. With its many

benefits, this econometric method has the ability to simultaneously estimate short-run dynamics and long-term relationships, which makes it well-suitable for modelling economic interactions that exhibit both immediate responses and lagged adjustments. Unlike traditional cointegration techniques that require uniform integration levels across variables, this model is applicable even when some regressors are stationary at levels, and others at first difference. This eliminates the chances of spurious regression which often encounters in non-stationary data environments, thereby enhancing the credibility and interpretability of empirical analysis.

Before selecting and applying the CS-ARDL model, it is required to conduct a series of pre-diagnostic tests to ensure that econometric methodology is appropriate for this panel data. Panel data are most prone to statistical issues of cross-sectional dependence, slope heterogeneity, non-stationarity, and long-run cointegration, all of which could distort the estimation outcomes if not addressed appropriately. Cross-sectional dependence is sourced from unobserved common factors that could affect all cross-sections, while slope heterogeneity represents the variation in parameter estimates across the units, and thus these both can violate the panel data assumptions. Therefore, it is required to use rigorous pre-estimation diagnostics, including Pesaran's CD test for CSD, the Pesaran and Yamagata test for slope heterogeneity, panel unit root tests (e.g., CIPS, CADF), and Westerlund or Kao cointegration tests, to ensure that statistical properties of dataset are appropriate for further estimation.

3.3.1. CSD Test

The present research utilizes multifarious methods to analyze cross-sectional dependence, including the CD test (the standard test, based on the work by Pesaran, 2015; Pesaran and Xie, 2021), the weighted CD test (CD_w) developed by Juodis and Reese (2022), and the CD_w⁺ test introduced by Fan et al. (2015). Traditional CD test allows to examine the cross-sectional dependence of variables by using the average correlation of residual across the cross-sectional units of panel study. On the other hand, CD_w test adds a weight matrix to the residual correlation, accounting for the assumption that there can be differences in the extent of dependence across the cross-sections, and allows for the estimation of dependent heterogeneous cross-sectional linkages. CD_w⁺ is more advanced one which strengthens test's power by detecting the weak cross-sectional dependence, especially in those panels having low signal strength. Equations (3) to (5) expresses CD test, CD_w test, and CD_w⁺ test:

$$CD = \frac{\frac{1}{N} \sum_{i=1}^N \sum_{j=1}^N \hat{\rho}_{ij}}{\frac{1}{N(N-1)} \sum_{i=1}^N \sum_{j=1}^N \hat{\rho}_{ij}} \quad (3)$$

$$CD_w = \frac{\frac{1}{N} \sum_{i=1}^N \sum_{j=1}^N w_{ij} \cdot \hat{\rho}_{ij}}{\frac{1}{N(N-1)} \sum_{i=1}^N \sum_{j=1}^N w_{ij} \cdot \hat{\rho}_{ij}} \quad (4)$$

$$CD_{w+} = \left(\frac{\frac{1}{N} \sum_{i=1}^N \sum_{j=1}^N w_{ij} \cdot \hat{\rho}_{ij}}{\frac{1}{N(N+1)} \sum_{i=1}^N \sum_{j=1}^N w_{ij} \cdot \hat{\rho}_{ij}} \right)^\alpha \quad (5)$$

In equations 3 to 5, N represents the number of cross-sectional units, $\hat{\rho}_{ij}$ denotes the residual correlation between the panels of study unit i and j , w_{ij} indicates the weight matrix of CD_w test, and α is the power enhancement parameter in CD_w⁺ test.

3.3.2. Slope heterogeneity test

In panel data analysis, it is crucial to account for the slope heterogeneity, as coefficient estimates could vary across the cross-sectional units. To address the issue of slope heterogeneity in panel data, this paper employs the Westerlund and Blomquist (2013) test, which is specifically designed to test for slope heterogeneity coefficients by comparing the dispersion of slopes to their respective standard errors. This test is applied for both fixed effects and random effects models, ultimately providing a robust assessment of heterogeneity across cross-sectional units. It is critical to establish the reliability and validity of this test to maintain comfort in the empirical results. As part of this process, this paper examines dynamic aspects of slope heterogeneity to account for the possibility that the slopes between the key variables may differ from one country to another. Formally, this can be expressed as follows:

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}} \left(2k \left(\frac{T-k-1}{T+1} \right)^{-\frac{1}{2}} \left(\frac{1}{N} \tilde{S} - 2k \right) \right) \quad (6)$$

where $\tilde{\Delta}_{ASH}$ is the adjusted delta and $\tilde{\Delta}_{SH}$ is the delta statistic of study.

3.3.3. The second-generation Unit root tests

To further confirm the existence of the stationarity in data, this study also employ second-generation unit root tests, which are specifically designed to account for the cross-sectional dependence, a very common issue in panel data. These tests are even better suited to testing for a unit root process in the context of a panel dataset, as they are specifically designed to accommodate cross-sectional dependence, which is frequently found in panel datasets. There are several tests available to examine the second-generation cross-sectional dependence, however, this study employs CIPS and CADF tests to identify the existence of stationarity of data in presence of cross-sectional dependence. The CIPS and CADF tests are formal extensions of the Augmented Dickey-Fuller (ADF) framework that can be implemented as augmented regression structures to account for serial correlation and cross-sectional interdependence. Their use in this analysis enhances the precision and reliability of any unit root diagnostics applied. The CIPS test can be formally specified as follows:

$$\text{CIPS}(N, T) = N^{-1} \sum_{i=1}^N t_i(N, T) \quad (7)$$

The CADF test is econometrically expressed:

$$Vt = b(1) + (\Delta x t - \mu x) + \varepsilon_t \quad (8)$$

3.3.4. Cointegration test

To confirm the existence of the long-term equilibrium relationship among the non-stationarity variables in a panel study, there is need to conduct cointegration test. Although traditional methods like the Dickey-Fuller t-test (Kao, 1999) and the Phillips-Perron t-test (Pedroni, 1999) are widely used, this study adopts the variance ratio test proposed by Westerlund (2007). This approach is particularly effective as it evaluates the relationship between short-term and long-term variances within the data series, offering a more dynamic and flexible framework to detect persistent equilibrium linkages across panel units. By focusing on variance components, the Westerlund test enhances the reliability of cointegration analysis even when there is cross-sectional dependence and heterogeneity exists among the variables of a study. This variance ratio test counteracts the limitations linked with traditional cointegration approaches as it is more flexible and robust framework to assess the cointegration under less restrictive conditions.

As such, it offers more accurate and reliable results to model long-term links among the study variables. The Westerlund panel variance ratio test (2007) can be econometrically expressed:

$$VR_p = \sum_{i=1}^N \sum_{t=1}^T \hat{E}_{it}^2 \left(\sum_{i=1}^N \hat{R}_i \right)^{-1} \quad (9)$$

3.3.5. CS-ARDL test

This study employs cross-sectional augmented autoregressive distributed lag (CS-ARDL) model, an advanced econometric approach to test the relationship among the variables in panel data study in presence of the cross-sectional dependence. This model extends the estimation accuracy by incorporating the cross-sectional averages into the ARDL framework, thereby directly mitigate the biases that arise mainly from ignoring the common shocks are correlated error structures across the panel units. The CS-ARDL approach, initially developed by (Chudik et al., 2011), extends the traditional bounds testing methodology for cointegration by accounting for the interdependencies across the cross-sectional units in a study. It is more suitable for macroeconomic and environmental datasets where unobserved global factors may have the influence on individual countries in correlated manner. In this study, CS-ARDL approach is employed to explore both the short-term and long-term impacts of CIRC, GET, and GGB on RP and EF. The analysis is based on panel data from 23 selected OECD countries covering the period 2001–2021. The CS-ARDL model is particularly suitable for addressing dynamic interrelationships among variables when there is existence of cross-sectional dependence and heterogeneity among the variables of study. This method has been widely adopted in recent empirical literature for examining sustainability dynamics (Alola & Kirikkaleli, 2019; Tiwari, 2024), making it a robust choice for the present analysis. This model is able to deliver robust estimations even when panel units are affected by the shared macroeconomic shocks or they exhibit heterogenous adjustment dynamics. Accordingly, the econometric specification of CS-ARDL model for this study can be expressed as:

$$Y_{it} = \sum_{i=1}^{py} \pi_{it} Y_{i,t} + \sum_{i=0}^{pz} \theta_{i1}^H Z_{i,t-1} + \sum_{i=0}^{pT} \phi_{i1}^2 Z_{i,t-1} + e_{it} \quad (10)$$

Further, equations (11) and (12) are framed to estimate the mean group and long-term coefficients:

$$\hat{\vartheta}_{(C-ARDL)} = \frac{\sum_{i=0}^{pz} \bar{\theta}_{il}}{1 - \sum_{i=1}^{py} \pi_{il}} \quad (11)$$

$$\hat{\theta}_{\text{meangroup (MG)}} = \frac{1}{N} \sum_{i=1}^N \hat{\vartheta}_i \quad (12)$$

4. Analysis and findings

4.1. Descriptive statistics

Table 2 presents the summary statistics for the complete panel dataset of 483 observations for 23 OECD countries from 2001 - 2021. Figure 1 displays a graphical representation of these statistics. The mean values for each of the variables suggest range that is plausible and positive across the dataset. The lower standard deviation values for the majority of the variables also represents the limited dispersion around the mean, which demonstrates that the data values are relatively close to one another. This depicts a consistent distribution for the variables, and lends credibility to the dataset as reliable for further empirical research. As per the skewness statistics, we find that all variables of this study are favourably and positively skewed, excluding RP and GDP. Further, kurtosis statistics have shown that all variables have greater value than 3, and this ensures the fitness of variables for further analysis.

Jarque-Bera statistics have shown relatively high statistics, and this allows us to understand that there is normal distribution of data.

Table 2: Descriptive summary statistics

Statistic	RP	EF	GET	GGB	Circ	GDP	Ind	RD
Mean	3.280121	8.835186	293.2993	0.3564658	25.5616	10.48258	23.85835	2.157419
Median	3.334749	8.146327	28.66667	0.318	8.806	10.62384	23.55047	2.107617
Std. Dev.	0.2674511	3.861871	675.3485	0.2665179	48.81865	0.5740133	4.19048	0.8460255
Skewness	-0.044003	0.9939663	3.1136	1.342776	3.944769	-1.100997	1.24808	0.290547
Kurtosis	2.641219	3.435941	12.82622	5.564421	18.58251	4.50465	9.229089	2.470703
Jarque-Bera	2.746	83.36	2724	277.5	6139	143.1	906.3	12.43
Probability	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0020
Observations	483	483	483	483	483	483	483	483

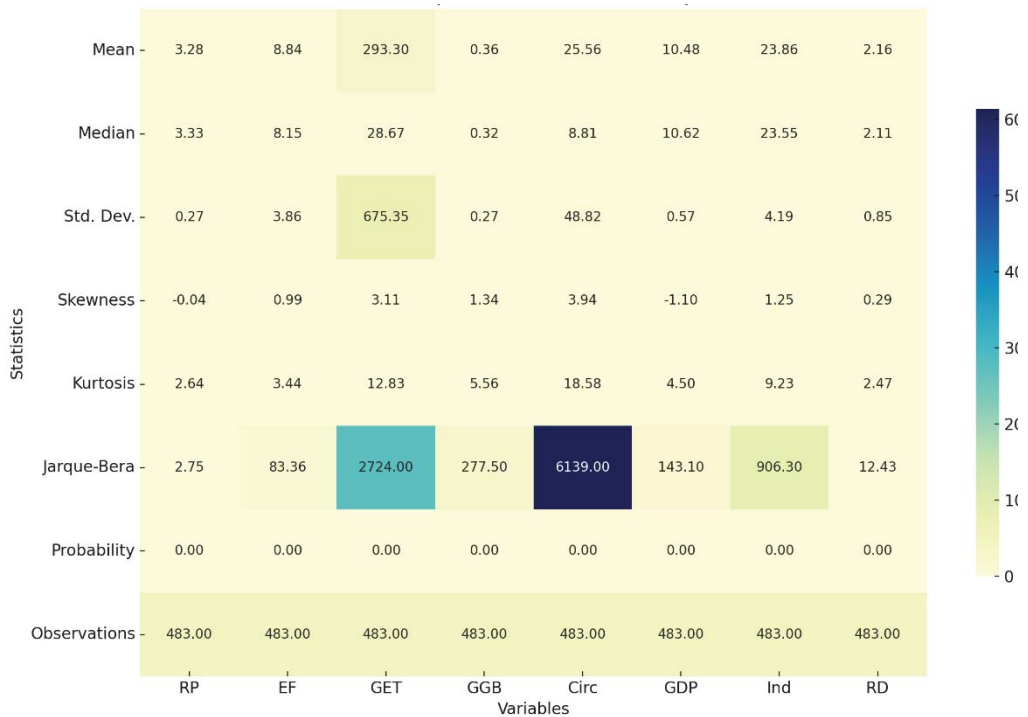


Figure 1: Descriptive statistics of variables

4.2. Cross-Sectional dependence results

The cross-sectional dependence results for all three tests, CD test, CDw test, and CDw+ test are presented in Table 3. Figure 2 visually presents the results of all three CD tests, applied in this study. The results of both the CD test and the enhanced CDw+ test provide evidence in favor of the alternative hypothesis, indicating the presence of strong cross-sectional dependence among the selected cross-sectional units in this study. This finding underscores the importance of employing econometric techniques that account for such dependence to ensure robust and unbiased estimation results.

Table 3: CD, CDw, and CDw+ test estimates.

Variables:	CD test	CDw test	CDw+ test
RP	37.04*** (0.000)	-1.32 (0.186)	841.09*** (0.000)
EF	41.26*** (0.000)	-1.65 (0.100)	953.02*** (0.000)
GET	48.01*** (0.000)	-1.68* (0.092)	760.84*** (0.000)
GGB	21.85*** (0.000)	1.38 (0.168)	478.97*** (0.000)
CIRC	10.64*** (0.000)	5.29*** (0.000)	619.15*** (0.000)
GDP	63.18*** (0.000)	-1.64 (0.101)	1003.33*** (0.000)
IND	17.96*** (0.000)	-0.43 (0.668)	425.52*** (0.000)
RD	28.39*** (0.000)	-1.48 (0.140)	665.77*** (0.000)

Note: P-values are presented in brackets, ***, **, and * indicate the significance level at 1%, 5%, and 10% respectively.

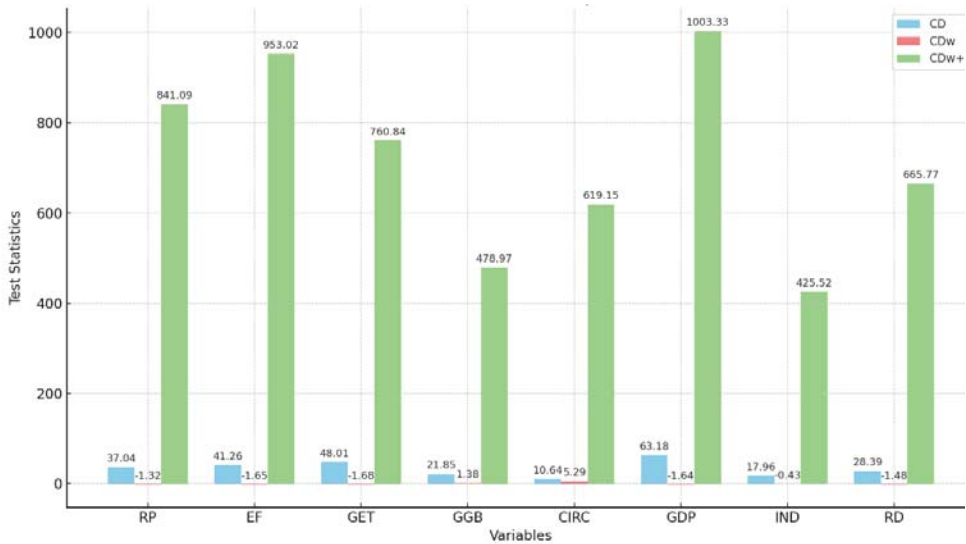


Figure 2: CD, CDw, and CDw+ visualization.

4.3. Slope Heterogeneity test estimates

Table 4 presents the slope heterogeneity estimates for both RP and EF models. As per the results, we find that Blomquist and Westerlund (2013)' both statistics of delta and adjusted delta has significance 1% for both of the models. These findings support accepting the alternative hypothesis that slope coefficients are heterogeneous in the cross-section, meaning slope heterogeneity exists. The null

hypothesis of slope homogeneity can then be rejected, confirming the necessity for econometric methods that account for slope heterogeneity in the panel.

Table 4: Results from the heterogeneity tests.

Parameters	Statistic	p-value
RP		
Delta statistic	11.006***	0.000
Adj. Delta statistic	13.988***	0.000
EF		
Delta statistic	11.093***	0.000
Adj. Delta statistic	14.099***	0.000

Note: * indicates the significance level at 1%.

4.4. Second-generation unit root test estimates

This study employs second-generation unit root tests of CIPS and CADF to examine the stationarity of the variables. Identifying the stationarity nature of data allows us to avoid the biased, inconsistent, and erroneous findings that may result in spurious regressions. We present the unit root statistics for all variables of this study in Table 5. The estimates for CIPS test and CADF test show that most of the variables of this study are stationary at levels, and become non-stationary at first difference.

Table 5: Second-generation unit root test estimates

Variables	CIPS (Level I(0))	CIPS (First Difference I(1))	CADF (Level I(0))	CADF (First Difference I(1))
RP	-2.254	-4.524***	-2.145**	-3.219***
EF	-2.055	-4.166***	-2.248***	-3.337***
GET	-2.807***	-4.894***	-2.032*	-3.580***
GGB	-2.222**	-4.774***	-1.746	-3.341***
CIRC	-1.384	-3.984***	-1.278	-2.660***
GDP	-1.559	-3.809***	-1.771	-2.619***
IND	-2.181**	-3.745***	-1.954*	-3.100***
RD	-1.955	-4.026***	-1.856	-2.372***

Note: ***, **, and * indicate the significance level at 1%, 5%, and 10% respectively.

4.5. Cointegration test results

This study applies the Westerlund (2007) cointegration test and results of this test are presented in Table 6. These results provide evidence that both RP and EF are statistically significant and have strong evidence of long-term cointegration among the variables studied. The results of the pre-diagnostic tests indicate the existence of slope heterogeneity, which leads to the acceptance of the alternative hypothesis that the slope coefficients are heterogeneous across panel units. These findings illustrate that econometric models that account for cross-sectional dependence and heterogeneous dynamics can be applied to analyze panel data. Additionally, the findings of CD-tests, unit-root tests, slope heterogeneity test, and cointegration test meet the criteria of CS-ARDL, and consider it as fit model for this study. Before moving to CS-ARDL test, we applied AIC approach and got the lag specifications for both models, which are presented in Table 7.

Table 6: The cointegration test estimates

Test	Statistics	p-value
RP (Variance ratio)	0.6741***	0.0025
EF (Variance ratio)	-0.2820***	0.0000

Note: ***, **, and * indicate the significance level at 1%, 5%, and 10% respectively.

Table 7: The selection of both models

Model	Log L	AIC	BIC	HQ	Specification
Model 1 (RP)	83.05498	-144.1100	-133.1569	-138.6335	ARDL (1,1,1,1,0,0,0)
Model 2 (EF)	17.78744	-13.57489	-2.621831	-8.098363	ARDL (1,0,0,1,0,1,1)

4.6. CS-ARDL Test results

The results of the CS-ARDL models are reported in Table 8, where two econometric models are estimated. Model 1 investigates the determinants of RP as a function of CIRC, GET, GGB, and control variables including GDP, industrialization (IND), and research and development (RD). Model 2 examines the impact of the same set of explanatory variables on EF. For Model 1, the short-run estimates reveal that CIRC, GET, GGB, and GDP exert positive and statistically significant effects on RP. In contrast, industrialization (IND) is the only variable found to have a significant negative influence on RP. These findings suggest that CIRC strategies, green technological advancement, and economic growth contribute positively to enhancing resource productivity in the short run, while increased industrial activity may hinder it due to its resource-intensive nature. Specifically, positive impact of GET shows that installing green technologies could be effective to enhance resource use efficiency, while GGB's short-term positive effect implies a positive role of government support to jumpstart green infrastructure projects. However, industrialization is found as the negative factor to influence the RP, due to using increased resource consumption. In long-run, CIRC, GET, and GDP continue to positively influence RP, and thus reinforce the argument that structural reforms, technology-led transformation, and sustained economic growth foster the RP in OECD countries over time. However, GGB's coefficient become negative in long-run, implying the inefficiencies in green budget allocations to garner the benefits of green budgeting for resource efficiency in OECD countries. Industrialization (IND) exhibit negative effects in long-run due to having the increased spending of resources by industry and thus negatively affect RP. However, RD exhibits positive effects in long-run, suggesting that R&D efforts are more likely to deliver the benefits in long-run only. Overall, the results confirm that CIRC initiatives have a positive and statistically significant impact on RP in the long run. This aligns with the findings of Tiwari and Mohammed (2024), reinforcing the argument that sustained CIRC efforts contribute meaningfully to enhancing resource efficiency over time. As per the estimates of GET, we found that it positively influences RP in short-term and long-term in case of OECD countries. As per these results, we can claim that technological innovations aid the countries to install efficient infrastructure that is more productive. GDP is remained positive for both, short-term and long-term horizons, suggesting its positive role to foster the sustainable resource consumption in OECD countries. Conversely, the negative impact of industrialization (IND) highlights the ongoing challenge of aligning economic development and industrial growth with sustainability objectives, underscoring the need for cleaner and more resource-efficient industrial practices.

The estimates from Model 2 provide empirical support for the Environmental Kuznets Curve (EKC) hypothesis. Specifically, the results show that in the short run, economic growth (GDP) has a significantly positive effect on the EF, indicating increased environmental degradation. However, in the long run, this relationship turns negative, suggesting that sustained economic growth contributes to improved environmental sustainability over time. This transition reflects the EKC premise that while

early stages of growth may strain the environment, mature economies tend to adopt cleaner technologies and more sustainable practices. The results of model 2 show that IND and GDP have the positive effects on EF in short-run, while GGB possess a negative impact on EF. These results imply that industrialization and economic growth foster the environmental degradation in short-run; however, government-green budgeting mitigates the environmental degradation in short-run. It can be claimed that industrial and economic activities contribute to EF, while GGB is the only factor to foster the ecological sustainability within OECD countries in short-term. In long-run CIRC, GDP, and GET present negative and significant coefficients, implying their constructive roles to achieve the environmental sustainability in OECD countries. IND present a positive coefficient in long-run, showing its constant role to promote the EF in OECD countries. The coefficient for GGB is positive but statistically insignificant, indicating that green fiscal policies may yield only limited or short-term effects in advancing ecological sustainability within OECD countries. These findings suggest that while fiscal interventions are important, they may not be sufficient on their own. Instead, CIRC practices and GET emerge as the more robust and consistent drivers in promoting resource productivity and reducing the ecological footprint in OECD countries.

Table 8: Benchmark estimates using CS-ARDL.

Variable	RP (Model 1)	EF (Model 2)
Long Run estimates		
CIRC	0.0087*** (3.12)	-0.2285*** (-3.95)
GET	0.0014*** (2.77)	-0.0063** (-2.23)
GGB	-0.0221*** (-4.37)	0.4769 (1.21)
GDP	0.0026*** (4.11)	-0.4725*** (-5.63)
IND	-0.0007* (-1.74)	0.0132** (2.40)
RD	0.0399* (1.93)	-0.2906 (-1.56)
Short Run estimates		
COINTEQ	-2.2527*** (-20.13)	-1.9402*** (-23.52)
D(CIRC)	0.0214*** (3.20)	-0.6379 (-0.93)
D(GET)	0.0011*** (2.92)	-0.0177 (-1.30)
D(GGB)	0.0024** (2.02)	-0.8261*** (-3.19)
D(GDP)	0.0116*** (4.25)	1.0708*** (4.78)
D(IND)	-0.0023** (-2.09)	0.0526*** (2.68)
D(RD)	-0.1205 (-1.03)	-0.0168 (-0.01)

Note: T-values are presented in brackets, ***, **, and * indicate the significance level at 1%, 5%, and 10% respectively.

In summary, CIRC posits a positive role to achieve the SDGs related to the more efficient use of resources and environmental sustainability in the OECD connotation. These findings are consistent with existing studies (Khan & Ximei, 2022; Zeng et al., 2022) that CIRC improves resource productivity and reduces carbon emissions through shared and cyclical frameworks of resource use. Similarly, GET was recognized as a consistently strong driver for resource efficiency in the short-term and long-term, across the spectrum of OECD countries (Middlemist & Hitt, 1981; Mohsin et al., 2021). The twofold contribution of GET illustrates the important role it plays in developing a resource efficient and sustainable infrastructure across the region. On the other side, these technologies promote the green production and processes across OECD countries, enabling greater ecological sustainability these countries. The estimates of GGB shows that it fosters RP and mitigates EF in short-term, however its impact is diluted in long-term (Garrone & Grilli, 2010). This could be due its delayed effects or having the institutional challenges to efficiently allocate the resources. These findings provide strong theoretical support for the principles of Ecological Modernization Theory (EMT), Innovation System Theory (IST), and Public Finance Theory. Collectively, they offer a robust conceptual foundation to validate the role of CIRC initiatives, GET, and GGB in enhancing RP and reducing EF (Hysa et al., 2020). These theoretical perspectives emphasize the potential of technological innovation, institutional transformation, and fiscal interventions in driving sustainable development. EMT conceptualizes CIRC as an institutional pathway to integrate ecological considerations into the economic systems through the mechanisms of eco-design, waste-resource loops, and industrial symbiosis, thereby promotes the decoupling between economic activity and environmental degradation (Andersen, 2007; Korhonen et al., 2018). These systemic innovations could be more relevant in context of OECD countries, where policy and market actors internalize the environmental and resource-oriented responsibilities (Goodwin et al., 2022; Shukla et al., 2025). IST theory accepts the role of GET, asserting that technological adoption could be driven by the interactions among the institutional structures, policy frameworks, and knowledge networks at macro-economic scale (Lundvall, 1992; Zhou et al., 2020). These technologies could reduce the environmental externalities while promoting the transparency and efficiency within OECD countries (Hekkert et al., 2007; Webster, 2015; Wijkman & Skanberg, 2015). From a fiscal point of view, public finance theory stipulates GGB as an institutional mechanism to operationalize sustainability through fiscal incentives, environmental budgets, and green infrastructural investments in OECD countries (DiMaggio & Powell, 1983; Miedzinski et al., 2022; North, 1990; OECD, 2022).

4.7. Robustness test results

To further confirm the robustness of baseline findings, this study employs Cross-Sectionally Augmented Error Correction Model (CS-ECM), which is a good alternative of CS-ARDL approach. Much like the CS-ARDL specification, the CS-ECM framework exploits the same pre-diagnostics procedures and provides estimates for both short-run dynamics and long-run equilibrium relationships (Sharif et al., 2022). The results presented below in Table 9 supports the results of the baseline estimates. Two drivers of long-run RP improvements among OECD countries, CIRC and GET remained statistically significant and robust over time. In contrast, GGB was negatively associated with RP in the long-run, which means it would have a limited impact, or possibly negative effect. Controlling for possible influences of other economic factors, GDP positively impacted RP in the short-run and long-run. Industrialization (IND) had a consistent negative effect on RP in both the short-run and long-run. Overall, the results of CS-ECM support the findings of the CS-ARDL, and thus allows us to believe in role of CIRC, GET, and GGB to foster RP and mitigate EF in OECD countries.

As per the robustness estimates for EF, this study finds that CIRC practices, GET, and GGB all exert negative and statistically significant effects on environmental degradation in both the short and long

term. This suggests that these policy and technological interventions not only have immediate impacts but also contribute to sustained reductions in ecological footprint over time. Therefore, it can be argued that CIRC, GET, and green fiscal allocations play a crucial role in promoting ecological sustainability within OECD countries. These results also support the EKC hypothesis, as economic growth (GDP) has positive coefficient in short-term, whereas negative coefficient in long-term, indicating the initially economic growth fosters the environmental degradation; however, in long-run it mitigates the environmental degradation. Overall, we can claim that CIRC, green enabling technologies, GGB have the robust effects toward RP in long-run in OECD countries. In case of model 2, we find that all, CIRC, GET, and government green budget allocations have their positive role to mitigate the environmental degradation in OECD countries.

Table 9: Robustness estimates using CS-ECM.

Variable	RP (Model 1)	EF (Model 2)
Long Run estimates		
CIRC	1.9657*** (3.83)	-1.4068*** (-4.46)
GET	1.351*** (4.69)	-1.0942* (-1.93)
GGB	-1.7341** (-2.19)	-1.242** (-2.33)
GDP	0.4326*** (5.83)	-0.3912*** (-3.05)
IND	-0.4352** (2.02)	-41.3940 (-0.36)
RD	-6.8772 (-0.34)	-5.779*** (-3.28)
Short Run estimates		
COINTEQ	-0.02189*** (-12.72)	0.01179*** (-18.42)
D(CIRC)	-0.0014 (-1.09)	-0.1651* (-1.72)
D(GET)	0.0081 (1.29)	-0.7923** (-1.98)
D(GGB)	0.0081 (0.29)	-0.5101* (-1.84)
D(GDP)	0.0048** (2.26)	1.0724*** (3.22)
D(IND)	-0.0014*** (-3.25)	0.0013 (0.05)
D(RD)	0.0126 (0.76)	0.3954 (1.37)

Note: T-values are presented in brackets, ***, **, and * indicate the significance level at 1%, 5%, and 10% respectively.

4. DISCUSSION AND CONCLUSION

Global environmental degradation and resource scarcity are among the most pressing issues of the 21st century, especially in OECD countries where material consumption and ecological footprints have surged. Using panel data from 23 OECD countries (2001–2021), this study applied the CS-ARDL model to examine how circular economy practices (CIRC), green-enabling technologies (GET), and government green budgets (GGB) impact resource productivity (RP) and ecological footprint (EF). Results show that CIRC and GET positively and significantly influence RP and reduce EF in both the short and long run. GGB improves RP only in the short run and has limited long-term effects on EF. The Environmental Kuznets Curve (EKC) is validated in relation to GDP's effect on EF. The robustness of findings is confirmed by CS-ECM analysis. The study is grounded in Ecological Modernization Theory, Innovation System Theory, and Public Finance Theory, supporting the argument that CIRC and GET are critical levers for decoupling growth from environmental harm, while the impact of fiscal tools depends on effective planning and institutional implementation.

First, the study highlights the essential role of CIRC in promoting sustainability and recommends incentives for waste reduction, resource recycling, and reuse. Policymakers should support CIRC adoption across industries to meet SDG targets. Second, GET demonstrates significant benefits for both RP and EF, suggesting that governments should prioritize investment in clean technologies throughout the lifecycle of infrastructure and industrial projects. Third, GGB shows only short-term effectiveness, indicating a need for better design, planning, and institutional oversight of green fiscal policies. Enhancing accountability and aligning expenditures with long-term ecological goals is necessary. Fourth, governments should adopt economic growth models that integrate green practices and technologies. Mechanisms like carbon pricing can internalize environmental costs and encourage low-carbon behavior. Lastly, given the diversity of OECD economies, a uniform policy approach may be ineffective. Tailored interventions based on each country's specific context—economic structure, resource challenges, and environmental goals—are more likely to yield impactful results. Countries should assess and adjust their green strategies to align with national capacities and priorities. Institutional mechanisms must be strengthened to support the efficient use of green budgets and ensure policy effectiveness. Moreover, collaboration among stakeholders, including public and private sectors, should be reinforced to promote sustainable innovation. These steps can help OECD nations transition toward a resource-efficient and ecologically balanced future.

Future studies should analyze sector-specific or regional-level data to provide granular insights. Incorporating institutional quality, policy enforcement, and innovation capacity as moderating variables could enrich the analysis. Expanding research beyond OECD countries to include emerging economies would offer comparative perspectives on sustainability strategies. The study's focus on CIRC, GET, and GGB leaves out other relevant factors such as public-private partnerships, carbon pricing, and governance quality, which future researchers should investigate. Additionally, while the EKC hypothesis was tested here, future work could examine the Low Carbon Curve (LCC) hypothesis to explore long-term decarbonization pathways. Addressing limitations such as omitted variables, country-specific effects, and sectoral heterogeneity would strengthen the robustness and applicability of future findings.

5. REFERENCES

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