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SUBMITTED: 12.01.2025, ACCEPTED: 21.03.2025, PUBLISHED ON-LINE: 01.07.2025
2025, 20(2): 223-245, DOI: 10.35784/preko.7059

The Effects of Circular Economy, Green Finance and ICT Developments on Resource Productivity aimed Ecological Sustainability: Evidence from OECD Countries Using a CS-ARDL Approach

Wpływ gospodarki o obiegu zamkniętym, zielonych finansów i rozwoju technologii ICT na produktywność zasobów ukierunkowaną na ekologiczną zrównoważoność: dowody z krajów OECD stosujących podejście CS-ARDL

Shaomeng Shi[1], Asad Nisar[2]

[1]Jilin Engineering Normal University, School of Art and Design,
3050 Kaixuan Road, Changchun City, Jilin Province, 130062, P.R. China
E-mail: ShaomengShi666@126.com, ORCID:0009-0000-8603-2748
[2]Central University of Finance and Economics, School of Finance,
Haidian, Beijing, P.R. China
Email: asadnisar@email.cufe.edu.cn

Abstract
OECD countries gained exponential economic growth over last two decades, now contributing over 60% of global GDP, however, this growth came with significant environmental costs, depleting natural resources at an alarming rate – material consumptions in these countries surged by 70% since 2000 – and raising critical question about these nations' role to achieve SDGs by 2030. To address the critical need of maintaining ecological sustainability and resource productivity, this study examines the interplay of circular economy (CE), green finance (GF), and ICT developments (ICT) across 27 OECD countries from 2000 to 2022. We utilize the CS-ARDL econometric approach to explain the short- and long-term effects of circular economy (CE), green finance (GF), and ICT developments (ICT) on resource productivity (RP) and ecological sustainability (ES). Findings reveal CE's dual impact, with initial short-term challenges – arising from resource-intensive infrastructure development – transforming into long-term benefits by reducing waste and improving resource efficiency. GF emerges as a robust driver, aligning investments toward green technologies and resource-efficient practices, fostering sustainability at scale. ICT developments exhibit a complex relationship, initially straining resources but later significantly enhancing RP and ES through advanced analytics, automation, and resource monitoring. Additionally, the study highlights the role of environmental policy stringency, showing that CE, GF, and ICT are more effective in enhancing RP and ES under tight environmental policies, whereas relaxed policies lead to weaker sustainability outcomes. This study underscores the critical role of CE, GF, and ICT in addressing pressing global sustainability challenges, offering actionable insights for policymakers and stakeholders.

Key words: circular economy, green finance, ICT developments, resource productivity, ecological sustainability, environment policy stringency

Streszczenie
Kraje OECD odnotowały wykładniczy wzrost gospodarczy w ciągu ostatnich dwóch dekad, przyczyniając się obecnie do ponad 60% światowego PKB, jednak wzrost ten wiązał się ze znacznymi kosztami środowiskowymi, wyczerpując zasoby naturalne w alarmującym tempie – zużycie materiałów w tych krajach wzrosło o 70% od 2000 r. – i podnosząc krytyczne pytanie o rolę tych krajów w osiągnięciu SDGs do 2030 r. Aby sprostać krytycznej

potrzebie utrzymania ekologicznej zrównoważoności i produktywności zasobów, niniejsze badanie analizuje wzajemne oddziaływanie gospodarki o obiegu zamkniętym (CE), zielonych finansów (GF) i rozwoju ICT (ICT) w 27 krajach OECD w latach 2000–2022. Wykorzystujemy ekonometryczne podejście CS-ARDL, aby wyjaśnić krótkoterminowy i długoterminowy wpływ gospodarki o obiegu zamkniętym (CE), zielonych finansów (GF) i rozwoju ICT (ICT) na produktywność zasobów (RP) i ekologiczną zrównoważoność (ES). Wyniki ujawniają podwójny wpływ CE, przy czym początkowe krótkoterminowe wyzwania – wynikające z rozwoju infrastruktury intensywnie wykorzystującej zasoby – przekształcają się w długoterminowe korzyści poprzez redukcję odpadów i poprawę efektywności wykorzystania zasobów. GF wyłania się jako solidny czynnik napędowy, dostosowujący inwestycje do zielonych technologii i praktyk efektywnego wykorzystania zasobów, wspierając zrównoważony rozwój na dużą skalę. Rozwój ICT wykazuje złożoną relację, początkowo obciążając zasoby, ale później znacznie wzmacniając RP i ES poprzez zaawansowaną analitykę, automatyzację i monitorowanie zasobów. Ponadto badanie podkreśla rolę rygorystyczności polityki środowiskowej, pokazując, że CE, GF i ICT są skuteczniejsze w wzmacnianiu RP i ES w ramach rygorystycznej polityki środowiskowej, podczas gdy złagodzona polityka prowadzi do słabszych wyników zrównoważonego rozwoju. Badanie to podkreśla krytyczną rolę CE, GF i ICT w rozwiązywaniu pilnych globalnych wyzwań zrównoważonego rozwoju, oferując praktyczne spostrzeżenia dla decydentów i interesariuszy.

Słowa kluczowe: gospodarka o obiegu zamkniętym, zielone finanse, rozwój ICT, produktywność zasobów, ekologiczna zrównoważoność, rygorystyczność polityki ochrony środowiska

1. Introduction

Since the 1960s, resource depletion and ecological disasters, such as resource reduction (Abbas & Dogan, 2022), land issues (Yang et al., 2022), global warming (Fu et al., 2022), and environmental degradation (Chien et al., 2021), are emerged as the urgent global concerns that require immediate action plans to deal with. The challenges of food crises, global warming, environmental pollution, and resource depletion are being faced by today's world (Pan et al., 2022; Shao & He, 2022). In response to these challenges, the United Nations introduced 17 Sustainable Development Goals (SDGs), focusing on affordable and renewable energy, climate action, resources conservation, and life on land (UNDP, 2021). The Paris Agreement, signed by 195 countries in 2015, is aimed at addressing global warming, climate change, and their alarming effects. It requires participation from all member countries to reduce greenhouse gas emission and implement strategies to adapt climate change. Despite the individual and joint ongoing efforts and international commitments of countries, CO_2 emissions are risen by 60% since 1992 signing of the United Nations Framework Convention on Climate Change (IEA, 2022), and 2020 is reported as one of the three warmest years of decade (Lindsey & Dahlman, 2022). Additionally, the excessive use of natural resources in industrial processes is another crucial contributor toward environmental pollution (UNEP, 2019). All these challenges underscore the immediate need for clean and environment-friendly production practices where resources could have been utilized wisely and ecological sustainability could also be ensured. According to the IPCC (2022) report, solely removing fossil fuel subsidies could lead the mitigation of carbon emissions by 4% and greenhouse gas emissions by 10%.

OECD countries hold substantial resources, including 60% of world' oil reserves, 50% of the world's natural gas reserves (IEA, 2021). The OECD bloc, including 37 countries, accounts for approximately 60% of the world's total GDP and 50% of global trade (OECD, 2021). This bloc has gained significant economic growth over the last two decades, and this growth is paralleled by a substantial increase in resource consumption, where total material footprint of bloc accounts for nearly 27 billion metric tones in 2019, highlighting the excessive use of resource to drive economic activities (OECD, 2022). This vast resource consumption underlines the importance of resource management efforts which could be in line with the sustainability goals of OECD countries. As shown in figure 1, increased resource consumption is leading the economic growth, but depleting ecological sustainability in OECD countries. In OECD countries, industrialization and accelerated economic growth have driven resource overexploitation, leading to environmental imbalances with serious consequences of air pollution, carbon emissions, global warming, and resource depletion. The OECD (2020) report stated that fossil fuels are more likely to be used as the dominating energy source due to the lack of green innovation and higher energy density of fossil fuels. Thus, OECD nations are in urgent need of accelerating their efforts to adopt circular economy practices, ICT and green finance development to maintain environmental sustainability. Investments in renewable energy, energy infrastructure, low-carbon automation, and digitalization are crucial solutions to support resource productivity and ecological sustainability. Advancing these all will encourage OECD to redesign resource management practices and mitigate negative environmental effects.

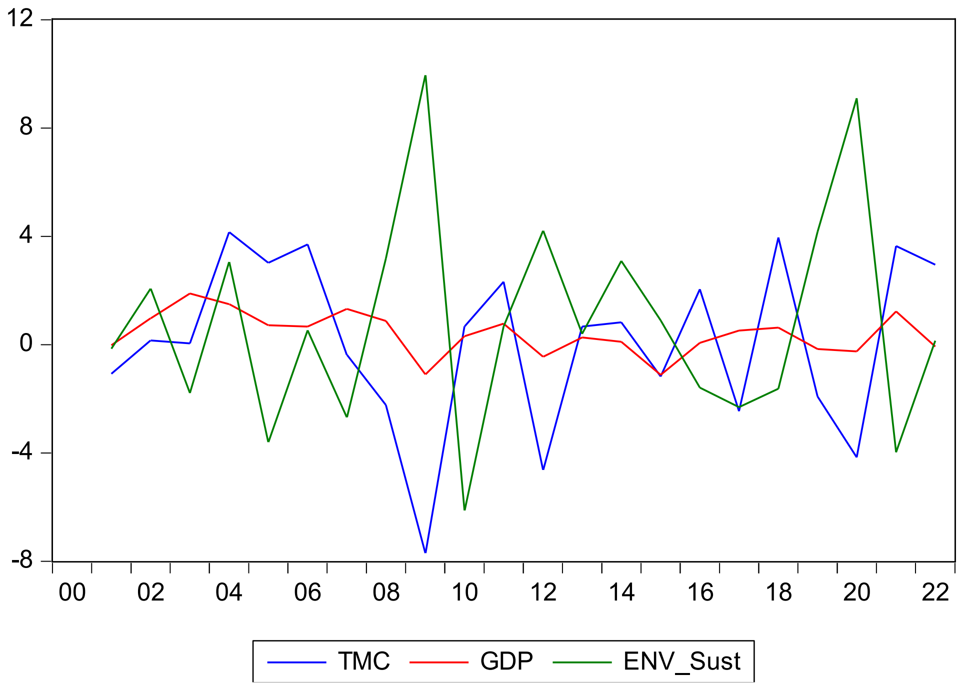

Figure 1. The nexus between Resource Consumption (TMC), Economic Growth (GDP), and carbon emissions (ENV_Sust)

To address these challenges, many countries shifted toward advancing their green economies (Lu et al., 2022). A green economy is focused to balance economic development, resource utilization, and environmental sustainability to be adaptive toward global climate changes and increased global risks (Song et al., 2022). Resource productivity is a crucial measure to assess a country's ability to resolve environment-related challenges, restore ecological performance (Najam & Malik, 2021), and support long-term economic sustainability (Goodwin et al., 2022). Therefore, advancing resource productivity is viewed as an essential solution for future economic development, and draws immense attention from academicians and policymakers (Goodwin et al., 2022; Pan et al., 2022). Additionally, countries are required to counteract the environmental challenges and ensure ecological sustainability. The key drivers of ecological sustainability include renewable energy consumption (Yao et al., 2019), industrialization (Rehman et al., 2021), green investment (David & Venkatachalam, 2018), forestry, agricultural finance development ((Koenker & Bassett Jr, 1978), non-renewable energy consumption (Awodumi & Adewuyi, 2020), and international trade (Belloumi & Alshehry, 2020). To reduce the adverse effects of climate change and environmental issues, countries are required to prioritize environmental sustainability and resource productivity by promoting green finance development, circular economies, and ICT development (Higón et al., 2017; Su et al., 2022; Tiwari & Mohammed, 2024; Umar et al., 2020). Aswathanarayana and Divi (2009) and Su et al. (2020) show that sustainable energy sources and advanced energy technologies are the ultimate solutions to frame green economies.

Circular economy (CE), green finance development (GF), and ICT developments (ICT) are essential to achieve environmental sustainability and sustainable development with minimal resource consumption (Lin et al., 2018; Wu et al., 2020; Wu & Sun, 2008). These concepts gained considerable interest from researchers, policymakers, and stakeholders in both developed and developing countries, especially in those who are pursuit of carbon neutrality and other sustainable developments goals. CE serves as the key tool to achieve environmental sustainability at regional, national, and global level. It gained significant attention from policymakers (European, 2015), researchers, and multinational enterprises (Lacy et al., 2014), as the effective solution to enhance environmental wellbeing (Gower & Schroeder, 2016b), and support productivity (Chertow & Park, 2016). CE includes the practices of product sharing, industrial symbiosis, repair (Chertow & Ehrenfeld, 2012; Lombardi & Laybourn, 2012), eco-design, remanufacturing, reuse (Nasr & Thurston, 2006), and refurbishment. Theoretically, CE is directly linked with other approaches such as industrial ecology, cleaner production, and sustainable production and consumption. Promoting CE could be crucial to achieve sustainable development by enhancing resource efficiency and safeguarding the environment. Additionally, European Union (EU) integrated recycling as the key component to achieve carbon neutrality, emphasizing the link between recycling and reducing greenhouse gas emissions. Institutional research also shows that adopting CE practices contribute up to 50% of carbon emissions' reductions (Wang et al., 2021). Some researchers also explained the nexus between circular economy and resource productivity, such as Yang et al. (2021) show that circular economy posits positive effects on various forms of productivity, including energy production, resource productivity, and green total factor productivity. Traditional theory argues that enhancing CE practices could lead to efficient resource consumption, and thus triggering a positive impact on overall productivity. He et al. (2010) employ *Kaya formula* to examine resource productivity by breaking it down into carbon emissions per unit of resource consumed and carbon productivity. Their findings suggest that advancing circular economy does not only foster resource productivity but also promote carbon neutrality. However, the effects of circular economy on resource productivity and ecological sustainability in OECD countries are not explained yet.

Green finance refers to a financial system that integrates environmental, social, and governance (ESG) considerations into a framework (Agrawal et al., 2024; Zhou et al., 2024). It mobilizes capital through instruments of green credit, green bonds, green insurance, carbon finance, and green funds, channeling these resources toward green industries, including environmental protection, energy conservation, and clean energy sectors (Berensmann & Lindenberg, 2016; Gilbert & Zhou, 2017; Lindlein, 2012). Green finance directs financial resources toward environmentally sustainable and socially beneficial initiatives while considering social and environmental risks into investment and financing decisions. Prior literature show that green finance works as the new financial model that merges economic development with environmental sustainability (Chen & Chen, 2021; Rizvi et al., 2022). From an economic growth perspective, green finance promotes economic structure optimization, and enhances capital allocation (Lee et al., 2022; Zhou et al., 2020). From ecological perspective, green finance encourages businesses to adopt advanced technologies and engage in sustainable production practices, thereby reinforcing social and environmental responsibilities (Hu et al., 2021; Xu & Li, 2020). Green finance introduces innovative financial tools designated to improve environmental quality and resource productivity (Su et al., 2022; Wang et al., 2019).

Information and communication technology (ICT) is a crucial key driver to support economic growth (Hoffert et al., 2002; Middlemist & Hitt, 1981), and promote digital economy (Khan & Ximei, 2022). Over the past few decades, ICT transforms the global economy by promoting productivity, boosting overall economic growth, and expanding global supply chains (OECD, 2000). The rapid decline in ICT equipment costs could lead to the substitution of traditional capital with ICT resources, increased efficiency, and lowered production costs. Responsible consumption and production, one of the 17 Sustainable Development Goals (SDGs) set by the United Nations (United, 2015), emphasizes the greater importance of the ICT sector to achieve sustainable development (Klimova et al., 2016). ICT serves as the catalyst across all three pillars of sustainable development and plays a crucial role to achieve all SDGs (Ga, 2015). ICT promotes efficiency, productivity, and sustainability by providing essential information and knowledge (Harris, 2013). The *green ICT* initiative minimizes the environmental impact of ICT operations by promoting sectoral efficiency and effectiveness while mitigating carbon emissions (Askarzai, 2011). ICT development cuts greenhouse gas emissions through the development of transportation systems, electrical grids, smarter cities, and industrial processes (Danish et al., 2017). The decline in ICT costs spur increased investments and facilitate restructuring of economic activities, including production processes (Jorgenson & Stiroh, 1999).

This paper makes several contributions to the existing literature. First, it is pioneering effort to explain the asymmetric relationship between circular economy, green finance, and ICT development in promoting resource productivity and ecological sustainability, using the CS-ARDL approach with data from 2000 to 2022 for OECD economies. To date, no prior research has collectively examined these variables in the OECD countries. Second, we conduct a throughout unit root analysis of key variables, including the circular economy, green finance, and ICT development, resource productivity, and ecological sustainability, using second-generation unit root tests to ensure robust stationarity checks. Third, by employing the CS-ARDL approach, an advanced version of the ARDL model, this study captures the asymmetries and provides deeper insights into the long-term association among the variables of current study. This paper emphasizes the role of circular economy, green finance, and ICT development as essential drivers of resource productivity and ecological sustainability. Finaly, this paper segregates the sample into countries with tight and relaxed environmental policies to evaluate the varying effects of CE, GF, ICT on RP and ES in OECD countries. The findings of current study offer practical insights for policymakers, governments, and other stakeholders to guide the development of policies aligned with green economy.

2. Literature Review and theoretical framework

The surge in resource consumption in OECD bloc underlies the need of improved resource management to achieve SDGs of resource productivity and carbon emission reductions. Over the past two decades, a significant increase has been observed in average material consumption per capita in OECD countries, such as it increased from 15 metric tons to 20 metric tons per capita over the period of 2000-2022 (Eurstat, 2023). This excessive growth did not strain natural resources but also led to environmental challenges of pollution and waste management. As per UNEP (2019), it is reported that inefficient resource consumption leads to economic losses of around 2% of GDP annually. Additionally, the OECD countries generate more than 30% of world's waste that significant contributes to the global environmental degradation (Schaffartzik et al., 2014). In such context, enhancing resource productivity is not only a regional need but a global imperative which requires coordinated efforts and innovative solutions (Jackson & Webster, 2016). The advancement in technology and processes has also been remained substantial over last two decades but the gap between resource consumption and productivity continues to widen, presenting a urgent necessity for strategic interventions (Schandl et al., 2018). The technological progress contributes to efficiency gains, but its advantages are offset by increased consumption driven by economic growth and consumer demand (Parrique et al., 2019).

The excess use of resource in OECD countries has raised serious concerns about environmental sustainability and economic efficiency. The OECD bloc, which includes most of the world's developed economies, are characterized by high level of resource consumption, and driven by urbanization, industrialization, and rising consumer demands. Studies show that OECD countries account for a signification portion of global resource consumption, leading to adverse environmental impacts of pollution, climate change, and biodiversity losses. Krausmann et al. (2009) show that material for OECD bloc is relatively high to the world, as contribution to over 40% of global material extraction despite representing only 18% of global population. This excessive resource consumption posits negative effects of increased greenhouse gas emissions and the depletion of non-renewable resources (Bringezu et al., 2004). In same stride, Wiedmann et al. (2015) note that ecological footprint of countries far exceeds their biocapacity, and thus resulting in ecological deficits. Additionally, studies show economic growth model employed by OECD countries often relies on unstainable resource consumption that exacerbate environmental degradation and contribute to global ecological crises (Hertwich & Peters, 2009; Steinberger et al., 2010). Therefore, to address unstainable resource consumption in OECD countries is crucial for achieve sustainable development goals through the mechanisms of circular economy, green finance, and ICT developments.

To promote sustainability at national and global level, the circular economy (CE) can offer promising solutions to resource management and environmental degradation challenges. The extraction of resources' figure is double globally over the period of 1980-2010, reaching at 72 gigatonnes (Gt), and is expected to reach at 100 Gt by 2030 (OECD, 2015). CE offers a crucial role to address waste management through promoting recycling practices. Countries like Mexico and Brazil, heavily rely on landfills for industrial and consumer waste, may benefit from CE-based recycling solutions (Tisserant et al., 2017). CE strategies focus many indicators of environmental sustainability, such as cleaner production, energy efficiency, pollution prevention, cleaner production, and environmental management, and thus CE directly addresses natural environment challenges (Baas, 2005). CE serves as an alternative development framework to foster ecological well-being, contributing to SDGs like SDG-6 (clean water and sanitation) and offering job opportunities (Gower & Schroeder, 2016a). CE practices facilitate sustainable consumption and production transitions (Schroeder et al., 2017), leading to cost saving, innovation, resource management, and job creation in both developed and developing countries (Ellen MacArthur, 2015; Friends of, 2014). As per recent estimates, CE could increase resource productivity by 3%, reduce net spending by by €600 billion, and generate €1.8 trillion annually by 2030 (Ellen MacArthur, 2015).

Additionally, CE could contribute to climate goals by recycling 6% of global resources and aiding in resource management. The European Union countries, essential part of OECD bloc, possess higher degree of circularity than the global average, have made significant progress, though further improvement needed (Haas et al., 2015). In Sweden, CE practices led to increase energy efficiency by 25%, promoting environmental outcomes (Sharif et al., 2023; Wijkman & Skanberg, 2015). Globally, CE initiatives reduced carbon dioxide by 7.5 billion tons through initiatives of shared ownership models, nutrient recovery, and chemical leasing (Ecofys & Circle, 2016). Recent forecasts indicate that recycling and waste reduction efforts could decrease carbon emissions by 424–617 million tons between 2015 and 2035 (EEA, 2016), with making significant contributions to various sectors. In the hospitality sector, CE actions are likely to reduce carbon emissions 100–200 Mt (EEA, 2016). In addition to sustainability-side benefits, CE creates job opportunities and thus offers significant economic contributions. For example, CE practices created 0.8 million jobs in France, that is almost 3% of country's total workforce (France, 2016). Similarly, by leveraging the benefits of CE, UK aims to create 517,000 new jobs through CE programs, including recycling and remanufacturing efforts (Morgan & Mitchell, 2015). These CE efforts are in line with the Paris Agreement goals, helping to close the gap to the 1.5°C climate change. Despite these benefits, a significant gap exists in current literature to present the environmental and resource benefits of CE practices in OECD countries. Bringing this gap is could explain the economic and environmental potential of CE; however, studies integrating CE with resource and environment management remain limited in both developed and developing countries, highlighting an area for future research.

The concept of green finance (GF) is not new in environment management research. Green finance development extends credit limits for high-emissions activities while offering low-interest rates to enterprises with low-emissions activities, and thus facilitating the rapid sustainable expansion (Aizawa & Yang, 2010). Zhou et al. (2020) examine the nexus between green finance, economic growth, and environmental quality, and show that green finance not only promotes environmental quality but also fosters economic growth. Similarly, Guo et al. (2022) demonstrate the role of green finance to reduce carbon emissions in China, finding that green finance directly mitigates environmental degradation. Using a sample of 26 Asian economies, Khan et al. (2022) report that green finance reduces carbon emissions, presenting its environment-friendly impact. Azhgaliyeva et al. (2018) emphasize the role of private investments in eco-friendly technologies to reduce carbon emission and promote a shift toward a low-carbon economy. Sharif et al. (2022) explain the positive role of green finance and technological innovations to reduce carbon emissions, stating that green funding and new technologies negatively influence carbon emissions. Moreover, Chen and Chen (2021) report that green finance development in China not only reduces carbon emissions in its targeted geographic areas but also benefits in surrounding regions.

Green finance may promote technological innovation by providing required funding for green processes, directing social capital flows, and supporting industrial structure upgrades through optimal resource allocation and strict regulations(Brock & Taylor, 2010; Greunz, 2004; Peneder, 2003). Both technological innovation and industrial upgrading serve as the crucial mediating mechanisms through which green finance development promotes resource productivity. Green finance fosters resource productivity in several ways. First, it offers a capital supply effect via channeling investments into green industries while restricting capital for high-pollution sectors, thereby improving resource efficiency. Second, GF drives technological innovation by aiding enterprises by diversifying innovation risks and focusing on green technological advancements. This targeted support allows high-efficiency and low-emissions' enterprises to get significant growth, whereas high-emission and low-efficiency enterprises would be gradually phased out of the market. Additionally, green finance ensures that funds are being closely monitored to guarantee that businesses are meeting the environmental obligations. In summary, research shows green finance promotes energy efficiency and contributes to carbon emission reductions (Yu et al., 2022). Al Mamun et al. (2022) and Zhang et al. (2022) confirm the positive role of green finance to promote environmental quality, however, Bilal and Shaheen (2024) state that green finance hinders banks' loan issuance, which could negatively impact investments in renewable energy and thus reduce environmental quality. Prior research focused on environment-related benefits and pitfalls of green finance; however, no one explained its influence on resource productivity, especially in OECD bloc. To bridge this gap, this study explains the effects of green finance on environmental quality and resource productivity in OECD countries.

Information and Communication Technology (ICT) serves as a key driving force of digitalization of production and transportation systems, directly promoting productivity. Nevertheless, ICT's environmental impact warrants careful consideration in addressing climate change challenge (Zhou et al., 2019). The environmental effects of ICT can be categorized into use effect, substitution effect, and cost effect. The use effect is referred to the ICT production cycles, including stages of production, processing, delivery, and maintenance (Shabani & Shahnazi, 2019). This cycle consumes substantial amount of electricity, and thus leads higher environmental degradation (Park et al., 2018). In many countries, ICT waste significantly contributes to carbon emissions due to limited waste management capabilities and technological resources (Khan et al., 2018). Next, ICT's substitution effect enhances production efficiency through the mechanisms of energy optimization (Coroama et al., 2012), decarbonization (Zhang & Liu, 2015), smart transport systems (Zhang et al., 2019), and electronic communication advancements (Shahnazi & Shabani, 2019). Last, the cost effect of ICT reflects market dynamics, where the need to meet rising demand increases environmental degradation (Shabani & Shahnazi, 2019).

ICT developments influence resource productivity through promoting the technological innovations. The technological innovations serve as critical driver of progress and efficiency improvement. Green enterprises are often technology or capital-intensive, and they require significant financial support to achieve and sustain high level of innovation. Green finance supports the technological innovations by prioritizing financing for the enterprises with low-carbon emissions, while increasing the borrowing costs for high-pollution and high-energy sectors (Asongu, 2013). This reallocation of capital encourages innovation within environmentally friendly firms, reducing energy consumption and carbon emissions per unit of output, and thus enhances overall long-term resource productivity (Liu et al., 2020). ICT developments possess direct contribution toward environmental quality and resource productivity; however, its potential influence on ecological sustainability and resource productivity in OECD countries is a crucial gap to explore, which is not studied yet, and focused by current study.

In summary, we highlight critical gaps in understanding the intersection of resource consumption, environmental impact, and sustainability initiatives within OECD countries. The surge in resource consumption in the OECD bloc emphasizes the urgency for improved management to meet Sustainable Development Goals (SDGs) related to resource productivity and carbon emissions reduction. OECD countries, consuming over 40% of global resources while accounting for only 18% of the world's population (Krausmann et al., 2009), face mounting environmental and economic challenges, including ecological deficits and GDP losses due to inefficient resource use (UNEP, 2019). Circular Economy (CE) and Green Finance (GF) emerge as promising frameworks for addressing these issues. CE initiatives focus on recycling, cleaner production, and sustainable consumption, which could enhance resource productivity and job creation (Ellen MacArthur Foundation, 2015). Meanwhile, GF promotes green technological advancements by directing capital towards eco-friendly industries, thus reducing carbon emissions and fostering sustainability (Zhou et al., 2020; Chen and Chen, 2021). Although ICT developments are transforming productivity, their environmental impacts – through use, substitution, and cost effects – require exploration, especially regarding resource productivity within the OECD context. This study aims to address these gaps by examining the comprehensive influence of CE, GF, and ICT on ecological sustainability and resource productivity in OECD countries.

3. Data, model, and methodology

3.1. Data

The baseline models for current study can be written as;
Resource productivity = (Circular economy, Green finance, ICT development, control variables); and
Ecological sustainability = (Circular economy, Green finance, ICT development, control variables).
In econometric terms, both models can be expressed

$$RP_{it} = \psi_0 + \psi_1 CE_{it} + \psi_2 GF_{it} + \psi_3 ICT_{it} + \psi_4 X_{it} + \vartheta_{it} \quad (1)$$

$$ES_{it} = \psi_0 + \psi_1 CE_{it} + \psi_2 GF_{it} + \psi_3 ICT_{it} + \psi_4 X_{it} + \vartheta_{it} \quad (2)$$

where RP_{it} is resource productivity, ES_{it} represents ecological sustainability, CE_{it} is circular economy, GF_{it} denotes green finance development, ICT_{it} is ICT developments, X_{it} represents list of control variables, ψ_1 to ψ_4 represent coefficients, ϑ_{it} denotes error term. This study examines the dynamic nexus of circular economy (CE), green finance (GF), and ICT developments (ICT), with resource productivity (RP), and ecological sustainability (ES) in selected 27 OECD countries, in time frame spans of 2000-2022. The selection of countries and study duration is purely based on the availability of required data to carry out empirical analysis. The selected OECD countries include Australia, Austria, Belgium, Canada, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Rep., Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkiye, United Kingdom, and United States. This study uses ICT service exports (BoP, current US$) as measure of ICT development, R&D expenditures (% of GDP) as measure of innovation, and GDP (constant 2015 US$) / Total material consumption as measure of resource productivity. Table 1 reports the measure, symbol, type and source of the variables. The control variables of this study are selected from relevant prior literature (Demirel & Kesidou, 2019; Krausmann et al., 2009; Tukker, 2015).

Table 1. Description of variables, sources

Type	Variable	Symbol	Measure	Source
Dep.	Resource Productivity	RP	GDP (constant 2015 US$) / Total material consumption	International Resource Panel, WDI World Bank
	Ecological Sustainability	ES	Biocapacity / Ecological Footprint (per capita)	Global Footprint Network (2023)
Ind.	Circular economy	CE	Municipal waste generation by million tons/year	OECD (2024)
	Green finance	GF	Budget spent on renewable energy public R&D.	OECD (2024)
	ICT development	ICT	ICT service exports (BoP, current US$)	WDI World Bank
Control	Gross Domestic Product	GDP	GDP per capita (current US$)	WDI World Bank
	Industrialization	IND	Manufacturing, value added (% of GDP)	WDI World Bank
	Trade	Trade	Trade (% of GDP)	WDI World Bank

3.2. Econometric methodology

Various statistical techniques employed in recent literature are tailored for panel data analysis. Current study employs panel data analysis to explain the effects of circular economy (CE), green finance (GF), and ICT developments (ICT) on resource productivity (RP) and ecological sustainability (ES) using data of OECD countries from 2000-2022. For the stated purpose, we employ econometric technique of CS-ARDL, to establish causal connection among the mentioned variables. The employed econometric techniques are integral to empirical economic research, aiding to understand and quantify the economic relationships, forecasting, and testing economic theories. Figure 2 offers a detailed illustration of the methodology and econometric approach employed in this study.

The Autoregressive Distributed Lag (ARDL) method is a time series econometric model to frame relationships among variables with different integration orders. ARDL presents both short-run and long-run effects within a single framework, making it highly useful to study economic interactions that exhibit both immediate and delayed effects of independent toward dependent variable. This model fits to those models where variables would have varying integration levels, such as it accommodates the cases where some variables are stationary I(0) (stationary) and others are I(1) (non-stationary). Using ARDL helps to mitigate the risk of spurious regression, which may occur when non-stationary time series variables are predicted together. ARDL's characteristic of integration addresses this issue and produces more useful and meaningful results. With the many advantages of ARDL, it is crucial to diagnose the potential statistical characteristics of panel data before moving toward the appropriate econometric approach that could provide reliable results. The potential key characteristics which could be commonly encountered in panel data analysis could be cross-section dependence (CSD), slope heterogeneity, data stationarity, and cointegration among variables. So, there is need to perform pre-diagnostic tests for being able to diagnose the statistical characteristics of panel data before selecting appropriate econometric model.

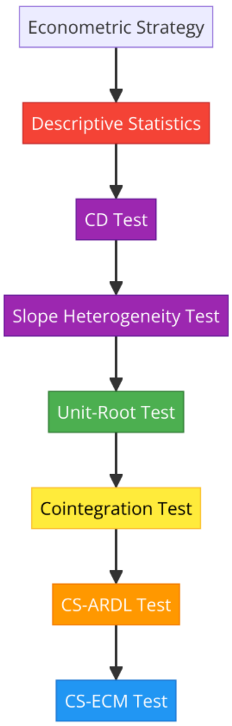

Figure 2. Econometric Strategy

3.2.1. CSD Test

To test CSD, this study uses numerous approaches such as CD (Pesaran, 2015; Pesaran & Xie, 2021), CDw (Juodis & Reese, 2022), and CDw+ tests (Fan et al., 2015). CD (Pesaran, 2015, 2021) is a traditional approach which is mainly used to measure the cross-sectional dependence via investigating the nexus of residuals across the cross-sections. The CD statisticis estimated as the ratio of the average pairwise correlation of residuals to the average correlation of squared residuals. CDw (Juodis & Reese, 2021) incorporates the weight matrix to enhance robustness by considering varying degrees of cross-sectional dependence. CDw+ (Fan et al., 2015) enhances the CDw by adding power proposed by Fan et al. (2015), aimed at improving the sensitivity of the CDw test for detecting cross-sectional dependence, especially in cases with weak signals. CD* (Pesaran & Xie, 2021) uses principal components (PCs) to address cross-sectional dependence by extracting PCs from residuals. These equations (1) to (4) present the equations for all of these CD tests:

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

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

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

In these equations, N denotes the number of cross-sections, $\hat{\rho}_{ij}$ represents the residual correlations between cross-sections i and j, w_{ij} indicates the weight matrix in the CDw test, α is the power enhancement parameter in the CD_{w+} test, and λ represents the eigenvalues of the principal components in the CD^{*} test.

3.2.2. Slope heterogeneity test

In any panel data study, accounting slope heterogeneity is crucial as slopes could be different across panel units. To address this, statistical test of the Westerlund and Blomquist (2013) test is employed by current study. The Blomquist and Westerlund test evaluates slope heterogeneity by comparing estimated slope coefficients and their standard errors, and can be applied both random and fixed effects models. The reliability and accuracy of these tests' results could be crucial to believe in outcomes of the panel data analysis. We examine the dynamic impact of the slope heterogeneity panel data (SHPD) issue, and can be mathematically as:

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

where $\widetilde{\Delta}_{ASH}$ and $\widetilde{\Delta}_{SH}$ represent adjusted delta and delta statistics, respectively.

3.2.3. Second-generation unit root test

To determine whether time series data possesses a unit root, we employ second-generation unit root tests. Since the presence of unit root reflects that a time series is non-stationary, this test helps to evaluate the stationarity of the series. Numerous statistical approaches are available for unit-root testing, such as CIPS test (Pesaran, 2007), the Im, Pesaran, and Shin (IPS) W-stat test (Im et al., 2003), the ADF-Fisher Chi-square test (Choi, 2001), the Levin, Lin, and Chu test (Levin et al., 2002), and the CADF test (Hansen, 1995). Using second-generation unit root tests accounts for cross-sectional dependence, and ensures accuracy and reliability of results. We apply CIPS and CADF tests, popular for their robustness, as these both tests rely on a basic linear regression model and able to handle serial correlation. These tests are expected to offer accurate estimates for further econometric analysis. The econometric form of CIPS test (Pesaran, 2007) can be expressed as follow:

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

The asymptotic properties of the CADF test (Hansen, 1995) are represented in Eq. (4).

$$Vt = \text{b(l)} + (\Delta\text{xt} - \mu\text{x}) + \varepsilon_t \quad (8)$$

3.2.4. Cointegration test

In panel data analysis, the cointegration test is crucial test as it identifies the long-term relationships among multiple non-stationary variables. There are several statistical methods available for cointegrating testing such as the Dickey-Fuller t-test (Kao, 1999) and the Phillips-Perron t-test (Pedroni, 1999), but we employ the variance ratio test (Westerlund, 2007). The Westerlund test evaluates the link between long-run and short-run variances of non-stationary series. We prefer variance ratio test over traditional cointegration methods, as it is more effective under certain conditions, and thus offers greater accuracy, especially when the data presents long memory or structural breaks. Traditional unit root tests have limitation of having low power in small samples and sensitivity to lag length selection. The variance ratio test serves as an alternative approach that is more robust to specific scenarios. The panel variance ratio statistic by Westerlund (2007) can be econometrically expressed as:

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

3.2.5. CS-ARDL test

The cross-sectionally augmented autoregressive distributed lag (CS-ARDL) econometric model is instrumental to examine the nexus among multiple variables within a dynamic panel data that consist of common or complex components. This model offers more precise parameter estimations by addressing the influence of shared characteristics on dynamic panels. The CS-ARDL test is applicable to panel data that includes multiple cross-sectional units observed over time and could be designed to account for cross-sectional dependence within such data. This approach extends the bounds testing approach of the ARDL cointegration method by accounting for cross-sectional dependence. Our study uses the CS-ARDL (Chudik et al., 2011), to explain the short-run and long-run effects of circular economy, green finance, and ICT developments on resource productivity and ecological sustainability across a sample of 27 OECD countries. This approach is widely applied in environmental studies (Alola & Kirikkaleli, 2019; Mohsin et al., 2021; Raskin, 1995; Tiwari & Mohammed, 2024), and allows to include potential cross-sectional effects. The CS-ARDL approach effectively captures both short-run and long-run effects, and econometric form of this model can be represented by this equation:

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

Further, equation (8) and (9) indicates the long-run and mean group coefficients, which could be reflected as:

$$\hat{\vartheta}_{[C-ARDL]} = \frac{\sum_{i=0}^{pz}\vec{\theta}_{il}}{1-\sum_{l=1}^{py}\hat{\pi}_{il}} \quad (11)$$

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

4. Analysis and findings

4.1. Descriptive analysis

The statistical finds for whole panel, that includes 598 observations for 27 countries over the period of 2000-2022, are presented in Tables 2, 3 and Figure 3. The mean values for all variables of current study are positive and within an acceptable range. The low standard deviation values for variables indicate that mean values are close to the data points for all variables of study. The skewness statistics show that all variables are favourably skewed, except for ICT and GDP. As per the kurtosis statistics, most of the variables are above threshold of 3, indicating the parameters possess heavier tails. Studying Jarque-Bera statistics show that test statistics are relatively high, reflecting not normal distribution of data. Figure 4 presents the visual trends of all of the variables over the sample period.

Additionally, Table 3 shows the mean change in explained variables RP, and ES, and explanatory variables of CE, GF, and ICT. As per the mean changes in each year in RP, it can be seemed that there is a significant improvement in resource productivity over the sample period. In case of ES, there is mixed pattern as in some years it is following upward trend, while in others it is decreasing. CE has shown stable trend over the period of 2000-2018, but in years of 2019 to 2022, its value reflects a downward trend. GF and ICT present increasing trends, reflecting the adoption of green finance and ICT tools by OECD countries.

Table 2. Descriptive statistics.

Statistic	RP	ES	CE	GF	ICT	GDP	Ind	Trade
Mean	2157.483	0.6269799	20.98225	107.6114	9.642592	10.36743	23.70493	88.79544
Median	1865.956	0.439744	5.5705	42.6375	9.712978	10.53987	23.53453	77.16978
Std. Dev.	1496.353	0.569444	40.92423	236.0532	0.6087196	0.638495	4.325637	44.14045
Skewness	2.096789	1.448525	4.372649	6.335976	-0.2592202	-0.841419	0.8240085	0.9466672
Kurtosis	9.349325	3.809425	22.83426	58.49212	2.62471	3.553548	7.765806	3.454862
Jarque-Bera	1443	225.4	12000	81000	10.21	78.2	633.6	94.47
Probability	0.000	0.0049	0.000	0.000	0.0061	0.017	0.0013	0.0021
Observations	598	598	598	598	598	598	598	598

Table 3. The mean change over time in explained and explanatory variables (2000-2022)

Year	RP	ES	CE	GF	ICT
2000	1674.068	0.626	22.282	36.051	9.149
2001	1753.681	0.621	21.697	40.242	9.175
2002	1803.916	0.634	21.963	43.842	9.179
2003	1840.304	0.615	22.071	43.665	9.249
2004	1837.500	0.605	22.293	48.064	9.343
2005	1822.654	0.572	22.424	51.896	9.402
2006	1798.560	0.599	22.632	55.561	9.496
2007	1867.251	0.569	23.246	78.787	9.573
2008	1949.532	0.581	22.933	76.443	9.629
2009	2052.455	0.649	22.614	192.350	9.609
2010	2087.324	0.596	22.637	159.202	9.629
2011	2070.563	0.601	22.677	174.113	9.686
2012	2178.087	0.626	22.475	183.958	9.697
2013	2190.801	0.621	22.467	163.639	9.761
2014	2241.862	0.641	22.616	136.026	9.803
2015	2350.022	0.662	22.868	131.300	9.779
2016	2371.834	0.648	23.498	115.808	9.808
2017	2505.562	0.627	23.542	106.972	9.858
2018	2517.882	0.619	24.483	117.555	9.916
2019	2638.002	0.651	13.934	130.884	9.948
2020	2638.884	0.707	14.228	121.337	9.979
2021	2706.947	0.677	14.339	130.530	10.052
2022	2724.417	0.673	8.673	136.836	10.059

Table 4. Cross-sectional dependence results.

Test	CD	CDw	CDw+
RP	47.88***	-1.44	1136.90***
	[0.000]	[0.149]	[0.000]
ES	32.28***	-0.25	828.82***
	[0.000]	[0.802]	[0.000]
ICT	78.12***	-3.00***	1405.39***
	[0.000]	[0.003]	[0.000]
GF	33.40***	-1.85*	681.97***
	[0.000]	[0.064]	[0.000]
CE	11.10***	0.48	634.24***
	[0.000]	[0.629]	[0.000]
GDP	74.17***	-1.89*	1334.68***
	[0.000]	[0.058]	[0.000]
Ind	21.55***	6.84***	591.26***
	[0.000]	[0.000]	[0.000]
Trade	53.37***	-1.43	1050.66***
	[0.000]	[0.153]	[0.000]

Note: ***, **, and * denote significance at 1%, 5%, and 10% respectively. P-values are shown in parentheses.

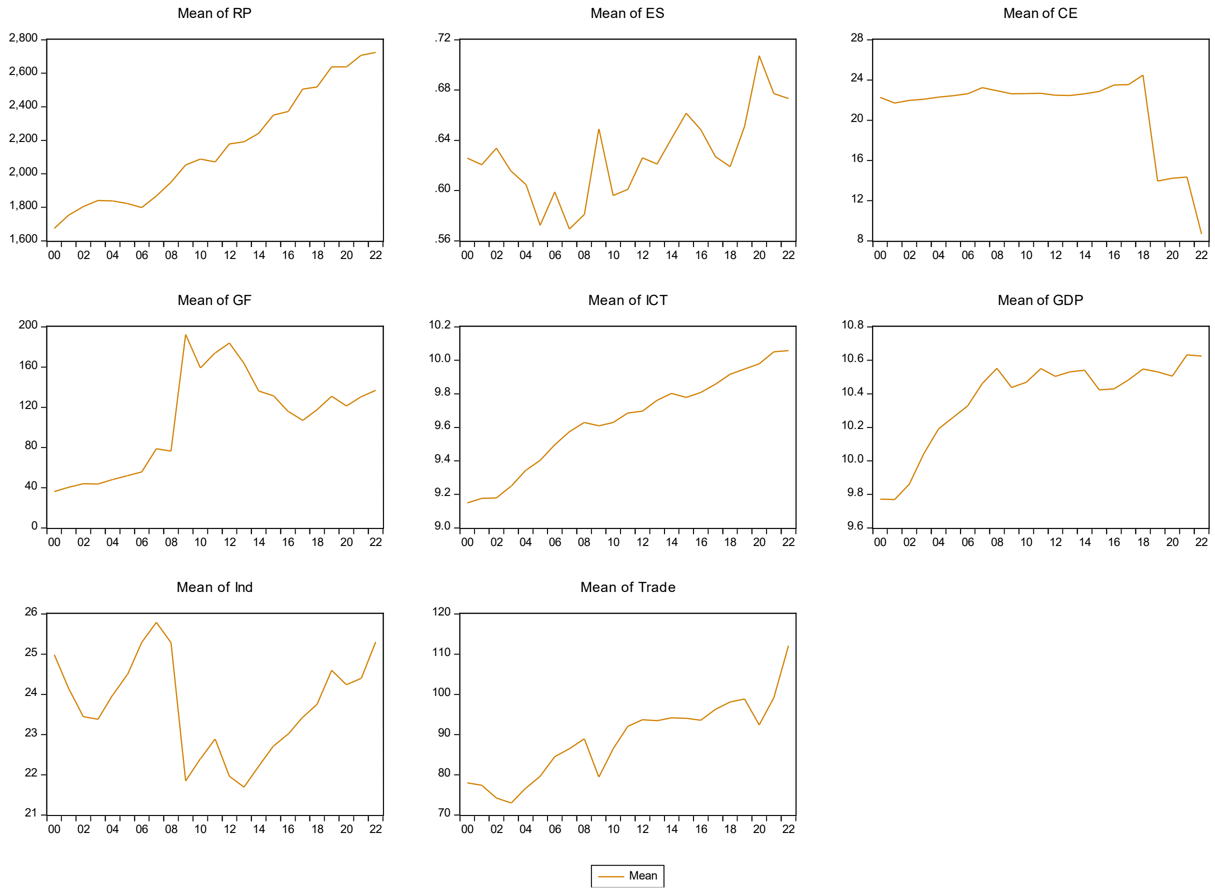

Figure 3. Trends of variables over the sample period

4.2. CSD test results

The CD statistics are reported in Table 4 and Figure 4. We utilize CD (Pesaran, 2015; Pesaran & Xie, 2021), CDw (Juodis & Reese, 2022), and CDw+ tests (Fan et al., 2015) to report the cross-sectional dependence results. The results support the alternative hypothesis of CSD in residuals and indicate that there is a strong cross-sectional dependence exists among the selected sample countries.

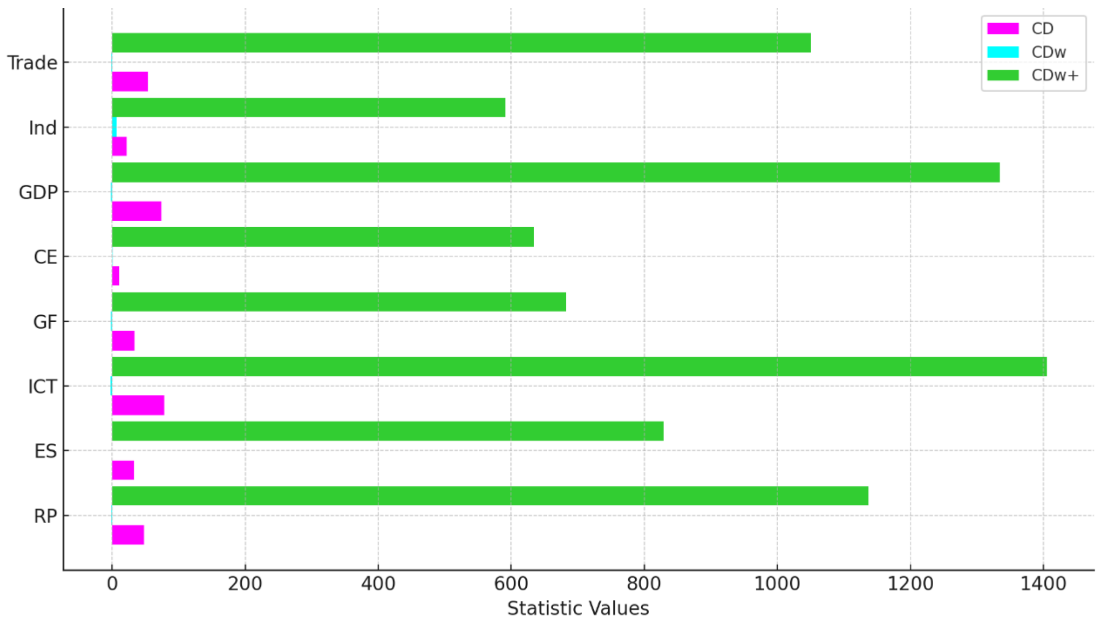

Figure 4. Cross-sectional dependence results for all variables of study

4.3. Slope heterogeneity test estimates

The results slope heterogeneity test for both models RP and ES are presented in Table 5. Utilizing the Blomquist, Westerlund (Blomquist and Westerlund, 2013) test shows that there is 1% of threshold of statistical significance for the delta and adjusted delta statistics for both models. Based on these estimates, we have to accept this hypothesis that slopes across the variables are heterogeneous and reject the null theory of variables being slope homogenous.

Table 5. Results from the heterogeneity test results.

Parameters	Statistic	p-value
RP		
Delta (Blomquist and Westerlund, 2013)	12.550*	0.000
Adj. Delta (Blomquist and Westerlund, 2013)	15.541*	0.000
ES		
Delta. (Blomquist and Westerlund, 2013)	45.072*	0.000
Adj. Delta (Blomquist and Westerlund, 2013)	55.812*	0.000

Note: * denotes significance at 1%.

4.4. Unit root test statistics

This study examined the stationarity nature of data in a process to avoid inconsistent, biased, and erroneous findings that could lead to spuriously regressions. The estimates of the unit root tests for all variables are presented in Table 6. We evaluated data stationarity at level (Level I(0)) and at first difference (First Difference I(1)) for both tests CIPS and CADF. As per the statistics of CIPS and CADF tests, we got validated estimates for all the variables at first difference. Only GF is found validated at level I (0), whereas all other estimates are found validated on other stages.

Table 6. Second-generation unit-root test results

Variables	CIPS (Level I(0))	CIPS (First Difference I(1))	CADF (Level I(0))	CADF (First Difference I(1))
RP	-2.314	-4.773***	-1.826	-3.595***
ES	-2.222	-5.523***	-1.790	-3.917***
ICT	-2.379	-3.893***	-2.574***	-3.612***
GF	-2.876*	-4.942***	-2.551***	-3.773***
CE	-1.043	-3.029*	-1.005	-2.075**
GDP	-1.759	-3.942***	-1.890	-2.823***
Ind	-1.840	-4.153***	-1.916	-3.331***
Trade	-1.687	-3.614***	-1.594	-2.879***

Note: ***, **, and * denote significance at 1%, 5%, and 10% respectively.

4.5. Cointegration test estimates

The results of long-term cointegration test are shown in Table 7. This study employed Westerlund, (2007) cointegration test to present variance ratio for both models RP and ES. As per the findings, RP has highly significant statistic while ES has statistical significance at 5%. Overall, variance ratios for both models reflect long-term cointegration among variables. Overall, pre-diagnostic estimates show slopes are not constant in our study and we have to accept the alternative hypothesis that the slopes are heterogeneous. All other estimates such as CD test results, Second-generation unit root test results, and Cointegration test results, also support the proper panel CD-ARDL model. In addition to this, before moving ahead to CS-ARDL testing, lag specifications are presented in table 8. Employing AIC approach, we got lag specifications of ARDL (1,1,0,1,1,1,1) for RP model, and ARDL (1,1,0,1,0,0,0) for ES model.

Table 7. Westerlund cointegration test results

Test	Test Statistics	p-value
RP (Variance ratio)	2.0100***	0.0060
ES (Variance ratio)	-0.5917**	0.0120

Note: ***, **, and * denote significance at 1%, 5%, and 10% respectively.

Table 8. Model selection criteria.

Model	LogL	AIC	BIC	HQ	Specification
Model 1 (RP)	-100.1247	226.2494	240.4330	232.1947	ARDL (1,1,0,1,1,1,1)
Model 2 (ES)	75.42568	-130.8514	-119.9409	-125.3962	ARDL (1,1,0,1,0,0,0)

4.6. CS-ARDL Results

The results of CS-ARDL model are reported in Table 9. This study tests two model; model 1 explains the effects of CE, GF, ICT, GDP, Ind, and Trade on RP, whereas model explains the effects of these the above-mentioned variables on ES. The results of model 1 indicate that in short-term, GF and GDP tend to be positive factor, while ICT, Ind, and Trade are the negative factors of RP. In long-term, CE, GF, and GDP positively influence RP, whereas ICT, Ind, and Trade negatively influence RP. These results support the view that circular economy offers its benefits toward resource productivity only in long-run and these results are in line with the findings of Tiwari and Mohammed (2024). The statistics of GF show that green finance development positively influence resource productivity both in short-term and long long-term. These results indicate that green financing channels the investments to develop resource-efficient infrastructure, which in turn offering the positive outcomes to boost resource productivity. In case of ICT development, it is found that it negatively influences resource productivity in short run, however, its long-term impact is positive. Similarly, the coefficients of GDP are found supporting to our findings, with positive results in both short-term and long-term. The results of industrialization and trade are also found acceptable showing that increase in industrialization and trade negatively impacts resource productivity through the channel of resource exploitation or resource consumption.

As per the estimates of model 2, first, we validate EKC hypothesis, which states that in short-run economic growth initially fosters environmental degradation, however, it turns to be environment-friendly in long-run. As per the estimates of GDP in short-run, the impact is found positive, whereas in long-run, its coefficient turns to positive side, validating the positive role of economic growth toward environment in long-run. The results of model 2 show that CE and ICT positively influence ES in short-term, whereas, GF, GDP, and Trade negatively influence ES in short-term. The long-term effects of CE, GF, and GDP are negative, whereas, ICT and Ind have positive influence toward ES, as shown in Table 9. According to these results, green finance is the supportive element to mitigate environmental degradation (ES) in both short run and long run. Circular economy promotes environmental degradation in short-run, however, its impact is found negative in long-run, suggesting that circular economy initially develops infrastructure which in turn depletes environment, however, after reaching at a threshold its impact toward environment become positive (Chen et al., 2021). As per the results of ICT developments, it is shown that ICT developments have their negative roles toward ecological sustainability in short-run. Its short-term effects are found positive toward environmental degradation, and thus validating the view that ICT developments promote such infrastructure which could have higher level of emissions at initial points. Additionally, the results of Ind and Trade are also found negative toward ecological sustainability.

Table 9. CS-ARDL Results.

Variable	RP	ES
	(Model 1)	(Model 2)
Long Run Equation		
CE	5.7757***	-0.0141***
	(3.28)	(-3.30)
GF	1.7346***	-0.0212**
	(5.68)	(-2.32)
ICT	7.5824***	-0.0104***
	(4.25)	(-4.93)
GDP	14.3024***	-0.0557***
	(5.13)	(-2.96)
Ind	-2.9451**	0.0041*
	(-2.39)	(1.67)
Trade	-1.3095*	0.0001
	(-1.73)	(1.04)
Short Run Equation		
COINTEQ01	-2.0040***	-2.1982***
	(-24.98)	(-32.88)
D(CE)	20.2835	0.0351**
	(1.41)	(2.24)
D(GF)	3.5667*	-0.0005**
	(1.67)	(-2.38)
D(ICT)	-1.7492**	0.0228***
	(-2.48)	(3.71)
D(GDP)	5.5149***	0.1298***
	(3.02)	(3.00)
D(Ind)	-12.7311*	0.0074
	(-1.77)	(1.49)
D(Trade)	-2.3908**	0.0004**
	(-2.56)	(2.13)

Note: ***, **, and * denote significance at 1%, 5%, and 10% respectively. t-statistics are shown in parentheses.

In summary, circular economy is found a positive factor to support the SDGs of resource efficiency and ecological sustainability in OECD countries. These findings are in line with the prior literature (Khan & Ximei, 2022; Sharif et al., 2022; Zhang & Liu, 2015), showing that circular economy through a shared model of resource utilization enhances resource productivity and mitigates the emissions of hazardous gases. Similarly, green finance posits robust effects toward resource efficiency and ecological sustainability. Its short-term and long-term effects are found highly supportive toward resource management and environment-friendly practices. In simple terms, green finance development promotes the resource efficiency through funding the green investment projects and thus leading the development of resource-efficient infrastructure. Green finance establishes such an infrastructure that enables more green products and green processes in OECD countries, and thereby enabling the ecological sustainability in these countries. ICT developments show mixed results, such as infrastructure based on ICT decreases resource productivity in short-term, however, it turns as a positive factor to boost resource productivity in long-term (Jiakui et al., 2023). In case of ES, ICT's role found negative in short run, while positive in long-run. As per the estimates, ICT developments lead to promote environmental degradation in short-run, whereas it posits positive effects toward ecological sustainability in long-run. It can be claimed that ICT developments develop such infrastructure which has its learning cost, and thus leading short-term negative effects toward environment. However, it promotes innovation in long-run and thereby promoting the ecological sustainability in long-run in OECD countries.

4.7. Robustness check

To confirm the robustness of benchmark estimates, we employ alternative model CS-ECM approach, that also requires similar pre-diagnostic estimates, as required by CS-ARDL

Table 10. CS-ECM Results

Variable	RP	ES
	(Model 1)	(Model 2)
Long Run Equation		
CE	9.3633***	-0.0433*
	(3.21)	(-1.82)
GF	3.5993***	-0.0432***
	(3.73)	(-3.56)
ICT	4.377***	-0.0617**
	(4.82)	(-2.43)
GDP	6.1718***	-0.4537*
	(2.71)	(-1.79)
Ind	-6.8967***	0.0181***
	(-3.98)	(2.68)
Trade	-1.2411***	0.0034
	(-2.78)	(1.44)
Short Run Equation		
COINTEQ01	-0.3227***	-1.2500***
	(-5.42)	(-8.69)
D(CE)	2.6058**	0.0819***
	(2.20)	(3.02)
D(GF)	3.1422***	-0.00004***
	(2.78)	(-3.04)
D(ICT)	-8.7533***	0.2007*
	(-3.48)	(1.67)
D(GDP)	1.4361***	0.1596***
	(5.46)	(3.28)
D(Ind)	-28.4749	-0.0022***
	(-1.14)	(-5.42)
D(Trade)	-1.4013	-0.0007***
	(-1.16)	(-2.26)

Note: ***, **, and * denote significance at 1%, 5%, and 10% respectively. t-statistics are shown in parentheses.

Approach, and results reported in Table 10. This statistical approach also present short-term and long-term effects for variables of current study (Sharif et al., 2022; Sohail et al., 2023). As per the results of model 1 (RP), circular economy's significant and positive role is found in both short term and long-term, and thus validating the baseline results, claiming the positive effects of circular economy toward resource productivity. The results of robustness test, validate the positive effects of green finance development toward resource productivity in short-term and long-term, and thus confirming the baseline results of CS-ARDL. ICT development's role tends to be similar as presented by CS-ARDL estimates, such as negative effects in short-run, whereas, positive effects in long-run toward resource productivity. Overall, the results of model 1 are found robust, and confirming the positive role of circular economy (CE), green finance (GF), and ICT developments (ICT) to foster resource productivity (RP) in OECD countries.

According to the CS-ECM estimates for ES, we find that circular economy (CE) posits short-term negative effects toward ecological sustainability in short-term, however, its impact turns to be positive in long-term. In simple terms, circular economy frames its positive effects toward ecological sustainability only in long-run, and thus validating the baseline results. As per the estimates of CS-ECM, green finance (GF)'s role is found supportive toward ecological sustainability in both, short-term and long-term. It can be argued that green finance is the robust factor to stimulate ecological sustainability and offering funds to establish a green environment. The CS-ECM results for ICT development (ICT) have also been found positive toward ecological sustainability in long-term only. Overall, the robustness test's results are in line with the findings of the CS-ARDL, and thus confirming the positive role of CE, GF, and ICT toward resource productivity and ecological sustainability in long-run.

4.8. Environment Policy Stringency: OECD countries Group analysis

This study also incorporates the effects of environment stringency policy to examine how circular economy, green finance development, and ICT develop influence resource productivity and environmental sustainability when this policy is tight or relaxed. Stringent environmental policies enforce regulations that encourage sustainable resource use, green innovations, and long-term economic and environmental sustainability (Porter & Linde, 1995). Countries with tight environmental policies shown a faster transition to sustainable development (Zhu & Lin, 2022), foster environmental quality (Mamghaderi et al., 2023), and extend circular economy practices (Tukker, 2015). Additionally, tight environmental policies encourage investments in green finance (Agrawal et al., 2024) and technology-based improvements (Higón et al., 2017). In context of OECD countries, environmental policy stringency may play a significant role to shape industrial and trade policies (Demirel & Kesidou, 2019), and support environmental sustainability (Grossman & Krueger, 1995). Table 11 reports the differentiated effects of CE (circular economy), GF (green finance), and ICT (information and communication technology developments) under varying environmental policy regimes. CE under tight environmental policies, significantly fosters resource productivity (RP) in long run as denoted by regression coefficient of 7.8143. In short-run, its impact is also found positive toward RP. Under relaxed environment policy, CE's magnitude of influence is lower such as 3.7372 in long run and 2.7876 in short-run. It shows that tight environmental policies lead the OECD counties to adopt circular practices of recycling and waste reduction, which further support their resource productivity. In case of ES, it is found that CE has larger negative affect on ES in long run as denoted by regression coefficient of -0.0736 under tight environment policies, and -0.0171 under relaxed environmental policies. It shows that CE fosters the ecological sustainability more effectively under tight environmental policies due to having costs associated for companies to install environmentally-inefficient plants or machineries. In short run, CE's impact is found positive, showing 0.000653 under tight policies and 0.0171 under relaxed policies. This indicates that CE's overall benefits toward resource productivity are ecological sustainability are greater for those countries having high environmental policy stringency. The strong role of CE to foster RP support the findings of efficiency (Macarthur & Heading, 2019; Tukker, 2015), who show that circular economy is a fundamental driver of resource efficiency.

The effect of GF to influence RP and ES vary based on environmental policy stringency. In long run, GF positively influence RP only when there are tight environmental policies, denoted by significant coefficient of 0.4060. This shows that green financial mechanisms could be more effective when reinforced by regulatory frameworks. GF with negative impact on ES is significant only under the tight environment policies. Under-relaxed environmental policies, GF's influence on ES is found insignificant. In short run, GF does not influence RP under either policy condition but negatively affects ES under tight policies, indicating that GF materialize its ecological benefits immediately, while its resource productivity effects are materialized in long-run. The positive impact of green finance (GF) toward ES and RP is in line with the findings of Iqbal et al. (2024) and Guo et al. (2022), who argue that green financial mechanism requires robust policy frameworks to be effective. ICT plays a crucial role to enhance RP in long run, as shown in Table 11, ICT has higher coefficient value under tight environmental policies than under relaxed environmental policies. This shows that ICT's role to drive efficiency and innovation is more effective when there are strong environmental regulations in place. In short run, ICT has negative and significant effects toward RP under tight policies only, showing that ICT works only under the tight environmental policies in short run. The negative effects of ICT toward RP could be due to the learning costs of the ICT technologies. In case of ES, it is found that ICT negatively influences ES, showing significant coefficient of -0.0613 under tight policies, while insignificant coefficient of -0.0120 under relaxed policies. This finding indicates ICT fosters the ecological sustainability in long run only when strict environmental policies are imposed in OCED countries. The short-run effects of ICT toward ES are also insignificant, suggesting that sustainability benefits of ICT take time to materialize and require policy support for effective implementation. ICT's nexus with RP and ES corroborates prior research by Khan and Ximei (2022) and Jiakui et al. (2023), showing that ICT initially increased energy demand, its fosters ecological sustainability and resource productivity in long-term.

Table 11. Environment policy stringency group analysis estimates

Variables	Tight Environmental Policy		Relaxed Environmental Policy	
	RP	ES	RP	ES
Long Run Equation				
CE	7.8143***	-0.0736*	3.7372**	-0.0171*
	(3.15)	(-1.92)	(2.04)	(-1.74)
GF	0.4060**	-0.0006***	2.8974	-0.0004
	(2.11)	(-3.37)	(1.33)	(-1.18)
ICT	7.2208***	-0.0613*	2.0668**	-0.0120
	(3.18)	(-1.70)	(2.14)	(-0.07)
GDP	5.7031***	0.2067***	3.1437**	0.3088**
	(3.60)	(2.74)	(2.29)	(2.55)
Ind	-19.2617*	0.0323	10.0085	-0.0045
	(-1.71)	(1.31)	(0.87)	(-0.34)
Trade	-1.2239**	-0.0029	0.1886	0.0018
	(-2.10)	(-0.50)	(0.10)	(0.86)
Short Run Equation				
COINTEQ01	-2.2077***	-2.3201***	-1.7550***	-1.0001***
	(-22.67)	(-7.108)	(-23.33)	(-6.235)
D(CE)	4.7875***	0.000653*	2.7876**	0.0171*
	(3.21)	(1.72)	(2.06)	(1.74)
D(GF)	1.0063	-0.0056*	5.1670	-0.0004
	(1.26)	(-1.77)	(1.23)	(-1.18)
D(ICT)	-4.6228***	-0.06132	-2.5494	0.0119
	(-3.38)	(-1.50)	(-0.09)	(0.07)
D(GDP)	2.4512***	0.20674***	5.1768**	0.3088**
	(3.57)	(2.74)	(2.34)	(2.55)
D(Ind)	-48.0228*	0.0323	-16.5751	0.0045
	(-1.69)	(1.31)	(-0.87)	(0.34)
D(Trade)	-1.2564	-0.0029	-0.6353	-0.0018
	(-0.24)	(-0.50)	(-0.20)	(-0.86)

Note: ***, **, and * denote significance at 1%, 5%, and 10% respectively. t-statistics are shown in parentheses.

5. Conclusion and policy implications

This study examines the effects of circular economy (CE), green finance (GF), and ICT developments (ICT) on resource productivity (RP) and ecological sustainability (ES) by using data of 27 OECD countries, covering the period of 2000-2022. Getting basis from pre-diagnostic estimates, this study employs CS-ARDL econometric approach to offer detailed understanding of how circular economy, green finance, and ICT development interact with resource productivity and environmental outcomes in the short and long-term. By testing both RP and ES models, we present the impacts of each explanatory variable across different economic conditions and time horizons. CS-ARDL results show distinctly positive effects toward resource productivity in long-term, suggesting a significant improvement in resource productivity and waste reduction. The long-term positive effects of circular economy imply that as circular economy practices are more embedded within OECD countries, they help in minimizing waste, promoting resource efficiency, and fostering more sustainable consumption patterns. However, circular economy's effects toward ecological sustainability present mixed results, as it has slightly negative impact in short term, while turning a positive factor in long-term. The initial negative impact is attributed to resource-intense requirements like with establishment of circular economy infrastructure, such as setting recycling facilities and systems to ensure materials recovery. Nevertheless, CE's impact turns to be positive in long-run, reinforcing the potential of CE strategies to mitigate environmental degradation once systems are operational and aligned with environmental goals.

As per the findings of current study, green finance (GF) is found as an influential and robust factor to promote resource productivity and ecological sustainability. The robust influence of GF underscores its importance to driver investments toward green and resource-efficient infrastructure, which, in turn, fosters resource-efficient practices. Green finance directs capital toward green technologies and environmental projects, and thus aids a shift toward a more sustainable industrial base, where financial mechanisms foster environmental stewardship. The dual and robust impact of green finance sets it a catalyst to align economic growth with environmental sustainability channeling investments toward projects that prioritize resource efficiency, lower emissions, and sustainable practices. ICT developments (ICT) possess complex relationship with resource productivity (RP) and ecological sustainability (ES). In the short term, ICT developments have a negative impact, suggesting that ICT infrastructure initially consume significant resources, particular due to high material requirements for ICT installation and high energy demands. However, in the long term, ICT development reflects a positive nexus with resource productivity, suggesting that once ICT systems are established and optimized, they can significantly boost resource efficiency by enabling advanced data analytics, automation, and resource-monitoring technologies that support productive and sustainable consumption and production of resources in OECD countries. Moreover, this study also validates the Environmental Kuznets Curve (EKC) hypothesis, indicating that economic growth initially promotes environmental degradation, however, as economies progress and adapt more sustainable practices, GDP's influence toward ecological well-being becomes more dominant. This study also incorporates the role of environmental policy stringency to examine the effects of CE, GF, and ICT on RP and ES by segregating the sample into countries with tight environmental policies and countries with relaxed environmental policies. The findings shows that tighter environmental policies enhance the positive effects of CE, GF, and ICT toward RP and ES in OECD countries. These findings emphasize the need of integrating policy interventions alongside technological and financial developments to maximize sustainability and resource productivity outcomes in OECD nations.

There are several policy implications, presented by the findings of current study. First, this study underlies the importance of green finance development, and suggests policymakers to prioritize green finance by channeling funds into sustainable projects, fostering ecological resilience, and promoting green investment channels to enhance resource productivity and ecological sustainability in the long-term. Second, policymakers are required to incentivize circular economy practices and focus on reducing waste and promoting resource recycling and reuse. Governments are required to introduce incentives for businesses to adopt CE models, so there could be significant contributions toward sustainable development goals (SDGs) by reducing waste and conserving resources. Third, governments should monitor ICT developments at initial level so there could be minimal learning costs, and there could positive contribution toward resource productivity and ecological sustainability throughout the lifecycle. Fourth, environmental policy stringency plays a critical role in determining the effectiveness of sustainability initiatives. Governments should adopt stringent regulatory frameworks to maximize the benefits of CE, GF, and ICT, ensuring that firms integrate sustainability into their operational models rather than relying solely on market-driven incentives. Fifth, policymakers are required to prioritize sustainable economic growth models that incorporate green technology and practices. For the stated purpose, there is need to introduce carbon pricing or similar economic mechanisms that can help in internalizing environmental costs, reducing the adverse ecological effects of economic growth. Last, governments in OECD countries to consider heterogenous nature, and there should be policy interventions to be customized for each country within the OECD countries to address specific environmental and economic dynamics. OECD countries to develop localized CE and green finance strategies that could reflect their unique economic, resource-richness, and environmental challenges.

Finally, with many contributions made by current study, still some limitations persist. This study examines the dynamic effects of circular economy, green finance, and ICT developments for resource productivity and ecological sustainability in OECD countries. This study presents the combined effects of these factors for a sample of 27 OECD countries. This would show that individual countries are not considered in this estimation. Thus, future researchers are encouraged to focus on individual country. Secondly, this study is limited to resource productivity and ecological sustainability through circular economy, ecological sustainability, and ICT development, there could be many other determinants of these both factors, which could be considered by future work. However, present study is focused on validating EKC hypothesis, whereas, future researchers may focus on LCC hypothesis and consider limitations of our work for better future research.

Acknowledgement

This paper represents the research findings of a key project of the Social Science Research Project of the Education Department of Jilin Province, project Title: *A Study on the Mechanism of School-Enterprise Collaborative Talent Cultivation under the Context of Supply-Demand Alignment in Employment for Environmental Design Majors* (Project Number: JJKH20240257S)

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