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The impact of eco-innovation on circular economy in EU countries: How patents affect circular material use rate?

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Abstract

PURPOSE*: The main objective of this study is to examine how eco-innovation activities, measured by the number of patents related to recycling and secondary raw materials, affect the level of use of circular materials in economic processes in European Union countries. Simultaneously, to take into account the impact of the other drivers of the circular economy, the study includes control variables such as GDP per capita, share of income from environmental taxes, age structure of the population, and level of education of the population.* **METHODOLOGY***: This study uses a generalized linear model for panel data. For all analyzed explanatory variables, greater inter-group variation than intra-group variation was observed, so a panel-averaged effects estimator was used. The study sample includes 28 European Union (EU) countries. The time scope of this study is 2010-2019. Eurostat database was the source of the unbalanced panel data. This study seeks answers to the following research question: What is the impact of patents related to waste management and recycling on the circularity rate of the EU economies?* **FINDINGS***: The results indicate that leaders in the area of circularity are the Netherlands, France, and Belgium. Ireland, Romania, and Portugal occupy last place in terms of the circularity of the economy. There is considerable variation in the number of patent applications related to waste management and recycling in the EU countries. Luxembourg, Finland, Belgium, and the Netherlands have the highest propensity for patents. In contrast, Bulgaria, Greece, and Croatia show the lowest patent activity. Finally, the higher the propensity to patent in waste management and recycling technologies, the higher the rate of circular use of materials.* **IMPLICATIONS:** *The results provide a compelling rationale for prioritizing and incentivizing investments in promising technologies to achieve both environmental sustainability and economic prosperity in the long term.* **ORIGINALITY AND VALUE***: Our study sheds new light on the link between eco-innovation and circular economy in EU countries. We address the issue of possible nonlinearities between circularity and its drivers. Given the fractional nature of the response variable (i.e., circular material use rate), we apply the generalized estimating equations (GEE) approach to model both the mean structure and association structure of fractional responses.*

Keywords: *circular economy, CE, circularity, eco-innovation, patent, circular material use, CE driver, EU countries, generalized estimating equations, recycling technologies, waste management*

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INTRODUCTION

The concept of the circular economy (CE) has been documented in scientific literature since the late 1960s (Boulding, 1966). However, the practical implementation and refinement of its basic principles began in the early 21st century. Initially, this took place in Asian countries, such as China and Japan, and then, as recommended in European Commission publications since 2014, in many European Union member states (Kulczycka, 2019). This concept has attracted increasing attention from policymakers, the scientific community, and economic practitioners alike (Ellen MacArthur Foundation, 2012; 2015, 2016; European Commission, 2015; 2020; Kirchherr et al., 2017; 2019; 2023a,b).

As each makes a distinct contribution to the development and use of the circular economy (CE), China and Japan are undoubtedly its pioneers. According to Arai et al. (2024), Japan is a pioneer in the adoption of CE policies, especially with regard to the Sound Material-Cycle Society, which prioritizes new technology over social justice considerations. China, on the other hand, has shown a significant increase in pilot projects and a top-down approach to resource management since incorporating CE into its political framework throughout the 1990s (Nemesh, 2022). Both nations have developed sizable frameworks for CE, with China emphasizing industrial applications and stakeholder involvement (Ogunmakinde, 2019) and Japan leading the way in end-of-life vehicle recycling with sophisticated legislation (Wang et al., 2021).

The European Commission's adoption of a new roadmap for a circular economy marks an important milestone in the implementation of the European Green Deal (European Commission 2019), a comprehensive strategy to achieve sustainable growth in Europe. This action plan includes various initiatives covering the entire product lifecycle. In particular, it focuses on aspects such as product design, promoting closed-loop economy processes, encouraging sustainable consumption, and maximising resource retention in the EU economy (European Commission, 2020).

Over the past decade, the number of publications on circular economic issues has increased significantly. The thematic scope of these studies mainly focused on the following:

- the essence and genesis of the CE concept (Kirchherr et al., 2017, 2019, 2023a,b; Prieto-Sandoval et al., 2018; Maksymiv et al., 2021; Gonçalves Castro et al., 2022);
- comparisons and relations of the circular economy with other concepts of socioeconomic development (Panchal et al., 2021; Triguero et al., 2021; Mirzyńska et al., 2021; Skvarciany et al., 2021; Santeramo, 2022; Sulich & Soloducho-Pelc, 2022; Simionescu, 2023);
- barriers and determinants of CE implementation (The Routledge Handbook of..., 2024; Munaro & Tavares, 2023; Aarikka-Stenroos et al., 2023; De Pascale et al., 2023; Thi-Kieu Ho et al, 2023; Neves & Marques, 2022; Arranz et al., 2022; Chiaroni et al., 2022; Hina et al., 2022; Kostakis & Tsagarakis, 2022; Tan et al., 2022; Harta et al., 2019);
- planning issues, including the formulation of CE development strategies at various governance levels (European Commission, 2015, 2020; Vanhamäki et al., 2021; Hartley, 2023; Purvis et al., 2023; Uvarova et al., 2023);
- promotion of good practices and models for circular economy implementation (Kopnina, 2019; van Langen & Passaro, 2021; Melles, 2023; Lisiecki et al., 2023; The Routledge Handbook of..., 2024;
- methods and evaluation of the effects of CE implementation (D'Adamo et al., 2024b; Banjerdpaiboon & Limleamthong, 2023; De Pascale et al., 2023; Matos et al., 2023; Kulczycka, 2020; Fura et al., 2020; Kasztelan, 2020; Moragaa et al., 2019; Palea et al., 2023).

One of the important areas of scientific interest remains issues related to the impact of eco-innovation (EI) on the dynamics of the processes of implementing the assumptions of the circular economy (Frone, 2017; Vence & Pereira, 2019; De Jesus et al., 2019; Stankevičienė & Nikanorova, 2020; Cainelli et al., 2020; Gomonov, 2021; Khaertdinova, 2021; Bucea-Manea-Tonis et al., 2021; Lehmann, 2022; Khan, 2022; Pichlak & Szromek, 2022; Platon et al., 2022;2023; Boonman et al., 2023; Rosca-Sadurschi & Șeremet (Ceclu), 2023; Bao et al., 2023). The correlation between CE and EI is readily apparent and it is doubtful that CE can be accomplished independently. However, the precise intricacies of this relationship need to be established. Not every aspect of EI is linked to CE, as not every aspect of CE necessitates innovation. Nevertheless, there is some overlap between the two. More specifically, in order to attain resource efficiency and minimize waste, there is a requirement for innovative waste management technologies (Cramer, 2015; Ghisellini et al., 2016; Lang-Koetz et al., 2010). These technological advancements should enable greater recyclability, thereby resulting in reduced waste compared with the current linear model of take, make, and disposal (Ness, 2008). Regrettably, the double externality predicament associated with the circumstance in which the entire society reaps the benefits of environmental innovation, while a solitary company bears all the costs independently (Rennings & Ziegler, 2004; Beise & Rennings, 2005), diminishes the motivations for corporations

to invest in such technologies. It is important to acknowledge that safeguarding inventions in the realm of waste management technologies and recycling by obtaining patents may offer economic inducements for corporations to commercialize their innovations (Habib et al., 2019). Conversely, there is a conflict between the rights of the patent holder and the necessity to utilize their environmentally friendly technology, which can be characterized as the "Green Patent Paradox," whereby patented technologies designed to mitigate the ramifications of climate change or replace environmentally hazardous industries may not realise their full potential partly due to patentees refraining from licensing their products (Cayton, 2020). Although green technology litigations are infrequent, Khan and Singh (2023) provide examples of crucial green technology litigations that underpin the patentability and granting of compulsory licensing of green technologies. They also analyze the link between green patenting and ESG practices. The latter are supposed to motivate firms to engage in green patent applications (Wang et al., 2023) and may provide useful information for professional and non-professional ESG investors (Škapa et al., 2022).

Achieving the goals of a circular economy requires significant technological and organizational changes. Simultaneously, to ensure the effective operation of circular economy models, it is necessary to use a systems approach to understand the impact of multiple interrelated factors that have different correlations and are constantly changing. Various elements of the system should be evaluated simultaneously.

Considering the above, the main objective of this study is to examine how eco-innovation activities, measured by the number of patents related to recycling and secondary raw materials, affect the level of use of circular materials in economic processes in European Union countries. Simultaneously, to take into account the impact of the other drivers of the circular economy, the study includes control variables such as GDP per capita, share of income from environmental taxes, age structure of the population, and level of education of the population.

The remainder of this paper is organized as follows. The Introduction section discusses the subject matter investigated. Subsequently, the Theoretical Background imparts a plethora of fruitful notions pertaining to the circular economy and its drivers. The sections concerning the Research Method disclose the provenance of the data and statistical methodologies employed in the research. The Results and Discussion section presents the outcomes and deliberates on the findings of previous studies, along with the unique perspectives acquired from the research results. Finally, the Conclusion section provides a concise summary of the findings.

THEORETICAL BACKGROUND

The concept of circular economy

In 2023, a group of scholars gathered around Kircherr (2023a), analyzed 221 definitions of the circular economy and formulated specific conclusions. First, it involves both consolidation and diversification. Second, definitional trends have emerged as potentially more relevant to science than to practice. Third, researchers are increasingly recommending fundamental systemic changes to enable CE, particularly within supply chains. Fourth, sustainability is often considered a central goal of CE, but uncertainty persists regarding whether CE can simultaneously promote both environmental and economic sustainability. Finally, recent research has shown that CE transformation relies on a broad alliance of stakeholders, including producers, consumers, policymakers, and researchers.

The most commonly cited definition of CE is that of the Ellen MacArthur Foundation (Kulczycka, 2019) – 'A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models' (Ellen MacArthur Foundation, 2012).

Kircherr et al. (2017) define CE as a peculiar economic system, pointing out that it operates at the micro (products, companies, consumers), meso (eco-industrial parks) and macro (city, region, nation, and beyond) levels, aiming to achieve sustainable development, thereby simultaneously creating environmental quality, economic prosperity, and social justice, for the benefit of current and future generations.

In comparison, the viewpoint platform Circular Academy perceives CE as an economic model that fundamentally alters the way production and consumption occur. Taking cues from the principles governing ecosystems and propelled by a design that aims to restore, this revolutionary system strengthens adaptability, eliminates inefficiency, and encourages the generation of mutually beneficial outcomes through an intensified circulation of both tangible and intangible streams (Circular Academy, 2023).

The European Commission, in its 2015 Roadmap for a Circular Economy (European Commission, 2015), instead states that the transition to a closed-loop economy, which aims to preserve the value of products, materials, and resources in the economic system for a longer period while minimizing the generation of waste, is a major undertaking by the European Union for a sustainable, low-carbon, energy-efficient, and competitive economy. Meanwhile, the 2020 revision of the document states that the European Union (EU) must expedite the process of transitioning towards a regenerative growth model that emphasizes returning more to the planet than it extracts. Additionally, it should actively work towards maintaining resource consumption within the limits of the planetary boundaries. Consequently, the EU should endeavor to diminish its consumption footprint and increase its circular material utilization rate twofold in the forthcoming decade (European Commission 2020).

Current definitions cover a wide range of explanations as to whether they address resource allocation (such as waste reduction and renewable energy) or economic aspects (such as transformative, regenerative, and value-creating economies). Although some definitions delve into combining circularity with a completely innovative approach to defining the economy, the basic concepts of these definitions focus exclusively on the circulation of resources and materials, thus allowing for further interpretation of the new regenerative economy.

Eco-innovation for circular economy

The term eco-innovation is used to categorize innovations that lead to a sustainable environment through the development and introduction of ecological enhancements (Kemp & Foxon, 2007). Reid and Miedzinski (2008) define eco-innovation with more precision. The latter needs to be linked to environmental issues, such as recycling and reuse. From an economic point of view, the most important peculiarity of eco-innovation is the so-called double externality problem. This problem is reflected by the fact that eco-innovations generate positive spillovers, that is, knowledge externalities and externalities related to positive effects on the environment. Both externalities cause suboptimal investments in eco-innovations (Losacker et al., 2023). This justifies the application of policy instruments (technology-push and demand-pull types) to provide the socially required level of investment in eco-innovation. Moreover, the double-externality problem may evolve into an appropriability problem because firms that introduce eco-innovations may experience difficulties benefiting from their generation. Ensuring the appropriability of profits from eco-innovations is possible thanks to secrecy, lead time, confidentiality agreements, complexity, and the intellectual property rights system, which includes patents granted for novel, non-obvious, and useful inventions.

Patents are a good means to measure eco-innovation. Patents are the exclusive monopoly rights granted to the owner of the invention. The number of patents related to environmental technologies (green patents) is often used to study both the innovative output and level of eco-inventive activities in particular technological fields (Oltra et al., 2010). Green patents are granted on technologies relating to waste, wind power, geothermal energy, solar energy, tidal energy, etc. (Khan & Singh, 2023). Favot et al. (2023) mention three approaches available to identify green patents based on the code classification: IPC Green Inventory, ENV-TECH, and Y02/Y04S Tagging scheme. From a CE perspective, within the green patents category, circular patents are most commonly identifiable as patents related to the main technological inventions for closing material loops, such as recycling and the application of secondary raw materials (Portillo-Tarragona et al., 2024).

Measuring eco-innovation is important for analyzing the economic and environmental consequences of green products and technologies. As suggested by Urbaniec et al. (2021), the neoclassical perspective seems particularly relevant for analyzing the role of eco-innovation in the economy when technological change is claimed to be an important source of development. Using this approach, eco-innovations are expected to lead to sustainable development owing to their contribution to technical progress, resulting in more efficient and responsible use of natural resources. R. Solow, one of the most important scholars of the "Neo-Classic Economics School", states that the authors load their case by letting some things grow exponentially, while others do not. Population, capital, and pollution grow exponentially in all models, but technologies for expanding resources and controlling pollution are permitted to grow, if at all, in discrete increments (Pansera, 2011, p.129). Within the neoclassical framework, pollution and environmental degradation result from externalized costs of industrial processes that can be minimized by eco-innovation. A prerequisite for such an influence of eco-innovation is a free market mechanism with environmental regulations to adjust for market failures. In this spirit, eco-innovation is regarded as a useful means to reenergize the sluggish economic growth of industrialized countries. In general, the impact of eco-innovation on industrial processes and consumption in the economy refers to three dimensions: energy, waste, and materials. The last two dimensions are extremely important from the CE perspective.

In a more general context, the scientific community agrees that eco-innovation is a basic condition for the development of a circular economy. Prieto-Sandoval et al. (2018) emphasize the significance of eco-innovations as a means of establishing a circular economy. They contend that comprehending eco-innovation from an ecological-centred viewpoint is essential for ensuring the practicality and prosperity of CE. Vence and Pereira (2018) indicate that eco-innovation plays a crucial role in driving the transition to a circular economy, with both technological and non-technological innovations being key. Similar conclusions are drawn by Pichlak and Szromek (2022), who indicate that eco-innovation, both technological and non-technological, acts as a catalyst for a circular economy. D'Adamo et al. (2024), on the other hand, find that technology plays a critical role in enabling an efficient closed-loop municipal waste management strategy that minimizes landfilling and other environmentally detrimental activities. By contrast, Cainelli et al. (2020) believe that environmental policy and green demand drivers are significant in promoting resource efficiency-oriented eco-innovations. Frone (2017) presents a study in which the strategic role of eco-innovation parks in promoting a circular economy is highlighted, particularly in the context of industrial synergy and regional metabolism. Edeh and Vinces (2023) study how different external sources of knowledge influence eco-innovation of small and medium-sized enterprises (SMEs) in developing economies. Their investigation reveals that the influence of outside information on eco-innovation differs and isn't always advantageous for businesses. Eco-product and eco-process innovation are strongly correlated with external knowledge from suppliers. On the other hand, eco-product innovation is favorably correlated with external consumer knowledge, but not with eco-process innovation. Horizontally, rival companies' external knowledge fosters eco-process innovation but not eco-product innovation.

It should be noted that eco-innovation contributes significantly to the development of circular economies in EU countries. This leads to progress toward sustainability by reducing the environmental impact of production, increasing resilience to environmental pressures, and promoting efficient use of natural resources (Rosca-Sadurschi & Șeremet (Ceclu), 2023). Gomonov's (2021) analysis confirms the importance of eco-innovation for CE in EU countries. The results show that the level of eco-innovation implementation varies across EU countries. Denmark and Sweden have emerged as unequivocal frontrunners, while Bulgaria, Cyprus, and Poland are making significant strides in catching up. Stankevičienė and Nikanorova (2020) propose the concept of measuring the development of eco-innovations in the context of the circular economy, with a focus on recycling, circular material usage, material efficiency, and waste management. Based on their analysis of the Baltic Sea region, the leaders in the eco-innovation ranking are Sweden, Denmark, and Germany, while Latvia, Estonia, and Poland are at the bottom of the pile. Technological and financial capabilities are essential drivers for all types of closed-loop economic activities in European companies, and public support is particularly important for recycling and process redesign (Triguero et al., 2021). Based on Platon et al. (2022, 2023), innovation in EU member states has a moderate and lagging effect on recycling. Eurozone membership has a positive impact on recycling and the circular economy. Eco-innovation and recycling play an important role in reducing the material footprint per capita and should be at the center of policies aimed at decoupling economic growth from raw material consumption. In the long run, by promoting eco-innovation and recycling, countries will minimize their demand for and consumption of raw materials.

Andre et al. (2015) find that the industry is closing the loop for some metals, and recycling-related patents play a significant role in influencing the use of closed-loop materials. Additionally, patents are seen as tools for new technologies in the transition to a circular economy, promoting advanced technologies, sustainability, and inventive activity (Khaertdinova et al., 2018; Khaertdinova et al., 2021). They contribute to the creation of new business opportunities and the development of circular economic centers. Recycling-related patents drive innovation and technological progress, supporting the transition to a closed-loop economy and sustainable use of materials (Jaakkola, 2019; Kostakis & Tsagarakis, 2022). Dume et al. (2022), in turn, emphasize that the selection and engineering of materials is a critical component towards the development of a circular economy model. Circular materials require a deliberate design that facilitates the full recycling of materials and innovative synthesis approaches that avoid the utilization of toxic precursors or the creation of undesirable by-products to restore the raw materials. Emphasizing more intelligent designs and conducting comprehensive analyses of the life cycle will shed light on the potential impact of circular material design on the development of a circular economy.

Based on these considerations, we formulate the following hypothesis: Eco-innovation, measured by patents related to recycling and secondary raw materials, has a positive impact on the circularity of EU countries.

Other drivers of circular economy

The process of implementing a circular economy depends on several conditions of different nature. The literature suggests the need to include economic and social factors in the analysis of the impact of patents related to recycling and secondary

raw materials on the use of circular materials in economic processes. These factors include GDP per capita, share of income from environmental taxes, age structure of the population, and level of education of the population.

Many scientific studies assume a positive relationship between GDP and the circular material use rate. Škare et al. (2023) find that income inequality is a barrier to circular economic development, indicating that higher GDP levels may be associated with higher circular material use rates. Kostakis and Tsagarakis (2022) also state that economic wealth positively affects material recycling and circularity rates. Grdić et al. (2020) conclude that the application of the circular economy concept can ensure economic growth and GDP growth while reducing the use of natural resources. On the other hand, Vuță et al. (2018) show that measures associated with the circular economy, such as the recycling rate of municipal waste and research and innovation expenditure, have positive effects on resource productivity and economic growth. In summary, these studies suggest that higher GDP levels are associated with increased circular material use rates. Wu et al. (2019), in turn, find that the GDP level has a significant impact on the rate of closed-loop material use. In general, the relationship between the GDP level and the rate of closed-loop material use is influenced by the principles of the closed-loop economy and the dynamics of economic cycles. However, one study by Pothen and Welsch (2019) suggests that there is a positive relationship between GDP per capita and material use, but this relationship becomes insignificant when endogeneity and nonstationarity are taken into account.

Another control variable is the share of income from environmental taxes. Environmental taxes, such as those imposed on incineration and landfills, have been found to have a beneficial influence on the utilization of circular materials by mitigating environmental repercussions and stimulating the practices of utilisation and recycling, thereby fostering a circular economy (Freire-González et al., 2022). This assertion is further corroborated by Kostakis and Tsagarakis (2022), who discern a positive correlation between the magnitude of environmental taxes and the recycling of materials as well as the level of circularity. Nevertheless, the efficacy of these levies may fluctuate contingent upon their formulation and implementation, as underscored by Walker et al. (2020), within the confines of a plastic levy. Aziz (2021) suggests that while the relationship between taxes and the circular economy is not consistent, there is a tenuous connection. Ojha and Vrat (2020) underscore the necessity of a transition from a linear model of resource consumption to a circular one, a transformation that could be expedited by environmental taxes.

The age structure of a population can significantly impact a circular economy in various ways. Struk and Soukopova (2016) investigate the correlation between the age composition of individuals residing in Czech municipalities, their per capita production of municipal solid waste, and their individual levels of waste separation. This study reveals that individuals in younger age brackets demonstrate superior performance in both dimensions. Conversely, individuals between the ages of 50 and 79 years exhibited the highest per capita production of residual waste and displayed the lowest levels of waste separation. Rybová and Slavík (2017) demonstrate that the generation of plastic waste is influenced by socio-demographic factors such as age. Ottelin et al. (2020) note that diverse household types encompassing varying age compositions manifest distinct patterns of circular consumption. Nevertheless, the association between these patterns and the overall material footprint may be tenuous, owing to the occurrence of rebound effects.

The last control variable included in the analysis is the population's level of education. Some studies collectively suggest that educational level has an impact on circular material use. Marouli (2016) emphasizes the need for education to promote circular and systemic thinking to achieve a circular economy and reduce waste generation behaviors. Pelău and Chinie (2018) find that a higher level of education positively influences the recycling rate of waste in an economy. Additionally, Kopnina (2019) highlights the importance of incorporating circular economy principles into business education to address the challenges of sustainable production. Finally, Ramli et al. (2021) discuss the need for students in higher education to adopt a circular economy approach in recycling and reusing study materials, indicating that technology can play a role in facilitating these practices. The level of education has an impact on circular material use. Higher education, such as a college degree, is associated with pro-environmental behaviours, including recycling (Loomis, 2020). Additionally, education can influence individuals' knowledge of conservation strategies and willingness to engage in environmentally friendly actions (Méndez-Giménez et al., 2012).

RESEARCH METHOD

We employ a generalized linear model to assess the effect of eco-innovation activities on the use of circular materials in economic processes in European Union countries. The level of use of circular materials is measured using the circular material use rate. The indicator is calculated as the share of material recycled and fed back into the economy, thus saving

the extraction of primary raw materials in overall material use. We apply eco-innovation activities, measured by the number of patents related to recycling and secondary raw materials, as the key explanatory variable. The other drivers of the circular economy serve as the control variables. These include GDP per capita, the share of income from environmental taxes, the age structure of the population, and the level of education of the population. Table 1 presents the responses and the explanatory variables used in the model.

The sample consists of 28 European Union countries (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom) from 2010 to 2019. As determined by the availability of data in the Eurostat Database, we deal with an unbalanced data set. Relying on a single data source avoids the potential issues related to data comparability. The choice of the generalized linear panel data model to assess the effect of eco-innovation activities on the use of circular materials in economic processes in European Union countries results from the nature of the response variable. The application of the fractional response variable arises with functional form issues. The logit and probit models are the most commonly used tools for fractional response variables. We use the generalized estimating equations (GEE) approach to model both the mean structure and association structure of fractional responses.

Table 1. Response and explanatory variables

No .	Variable name	Measurement	Symbol
Response variable			
1.	Circular materials use	Ratio of the circular use of materials to the overall material use	CIR
Explanatory variables			
2.	Patents	Number of patents related to recycling and secondary raw materials per million inhabitants	PAT
3.	GDP per capita	GDP per capita (in PPS_EU27 from 2020 = 100)	GDP
4.	Education level	Pupils and students having Bachelor's or equivalent level as % of total age population	EDU
5.	Total environmental taxes	Proportion of environmental tax revenues in total revenues from all taxes	TET
6.	Old-age-dependency ratio	Ratio between number of persons aged 65 and over and number of persons aged between 15 and 64	OAD

GEE is a method developed by Liang and Zeger (1986) for estimating the parameters of generalised linear models, which are also known as population-averaged panel-data models. It offers a robust approach for accounting for dependencies among observations within a dataset. GEE adopts a quasi-likelihood approach, focusing on estimating the average population parameters, and does not require complete specification of the joint distribution of the data, making it less sensitive to distributional assumptions and robust to misspecifications.

We have available t observations, $t = 1, 2, \ldots, T$, for each subject i, $i = 1, 2, \ldots, N$. The response variable was y_{it}, $0 \leq y_{it} \leq 1$, and the outcomes at the endpoints were zero and one. The explanatory variables were included in a 1 x K vector, $\mathbf{x}_{it}$. For the mean response, the generalized linear model is specified as follows: , i -= 1, 2, …, N; t = 1, 2, …, T, where g() denotes the link function. The GEE method accommodates a wide range of models by allowing flexibility in the specification of the dependent variable distribution and the choice of the link function. For a normally distributed dependent variable y_{it} and an identity link function, the model reduces to linear regression. When y_{it} follows a Bernoulli distribution with a logit link function, the result is logistic regression. Similarly, for y_{it} with a Poisson distribution and a natural log link function, the model corresponds to Poisson regression, also known as a log-linear model. If y_{it} is a fractional variable, as in our case, an appropriate choice of g() is either a logit or probit function.

The GEE procedure declares the within-group correlation structure, reflecting the assumed dependence among observations in the correlation matrix. Common choices include exchangeable, autoregressive, and unstructured correlations. The exchangeable correlation structure assumes that the correlation between any two observations within the same individual is constant, irrespective of the time points at which the observations are recorded. This implies that all off-diagonal elements of the correlation matrix are equal, while the diagonal elements are fixed at one. The autoregressive correlation structure assumes that the correlation between two observations is a function of their lag and it decreases as the time between them increases. The unstructured correlations make no specific assumptions about the pattern of correlations, allowing each pair of observations to have a unique correlation. While highly flexible, this approach can be computationally

intensive and may require a large sample size to estimate the numerous correlation parameters reliably. GEE estimation involves iteratively estimating model parameters using a sandwich estimator to account for within-cluster correlations.

RESULTS AND DISCUSSION

Following the procedure described in the previous section, we identified the key factors determining the development of circular materials in economic processes. Table 2 presents the descriptive statistics of the variables used in the survey and the panel decomposition of their standard deviations. The average circular use of materials in the 25 EU countries increased from 8.2% in 2010 to 9.7% in 2019. The lowest average levels of this indicator were observed in Ireland (1.8%), Romania (2.1%), and Portugal (2.1%). In turn, the highest average values of the indicators were in the Netherlands (27.3%), France (18.3%), and Belgium (18.1%). It should be noted that our results are generally in line with those of other studies that use a circular economy index to measure the progress of European countries in their transition towards CE. For example, Mazur-Wierzbicka (2021) finds evidence of a two-speed Europe in relation to the advancement of European Union member states in pursuing operations according to CE principles. The countries with the highest CE index values include Germany, Belgium, Spain, France, Italy, and the Netherlands. The second group of countries with the slowest pace of transformation towards CE is formed by Cyprus, Czechia, Malta, Lithuania, Latvia, Hungary, Ireland, Slovakia, Romania, Estonia, Croatia, and Bulgaria. Interestingly, Claudio-Quiroga and Poza (2024) and Pintilie (2021) appreciate that there is a four-speed Europe in terms of the circular economy concept, highlighting the good results of the Netherlands, Germany, Italy, and Belgium.

The number of patents, which is the key explanatory variable, varies significantly between countries. The average value ranged from 0.66 in 2010 to 1.15 in 2014, whereas the standard deviation ranged from 0.75 in 2011 to 2.23 in 2014. The coefficient of variation for the entire period was 153%, indicating very large differences. The countries with the lowest average value of the indicator include Bulgaria (0.054), Croatia (0.070), and Greece (0.093). By contrast, the group of countries with the highest average value of the indicator consists of Luxembourg (6.404), Finland (3.039), and the Netherlands (1.453). In the case of countries like Bulgaria and Croatia, their low propensity to patent may result from the fact that these countries have significantly less R&D personnel and researchers in the share of total employment as well as governments environmental and energy R&D appropriations and outlays compared to such countries as Luxemburg, Finland, and the Netherlands. Fura (2020) stresses the leading role of Luxembourg in patenting the field of recycling and secondary raw materials. From an international perspective, Europe and the US are the leaders in innovation in plastic recycling and alternative plastic technologies. Europe and the US each accounted for 30% of patenting activities worldwide in these sectors between 2010 and 2019 (European Patent Office, 2021b). Within Europe, Germany has the largest absolute number of international patent families (IPFs). However, this situation reflects the size of the German economy rather than a real specialization in plastic recycling technologies. Among smaller European countries, the Netherlands has a strong technological specialization in plastic recycling, which is reflected in Dutch companies' prominent positions in the recycling industry (Hanemaaijer & Kishna, 2023).

Analysis of the panel structure of the data shows that for each variable, the between-group variation is much larger than the within-group variance. Therefore, we use a generalized estimating equation to estimate the parameters of a generalized linear model with a possible correlation between observations at different time points.

As previously mentioned, we apply GEE to estimate the population-averaged effects of eco-innovation activities on the use of circular materials in economic processes in European Union countries. We employ a working correlation matrix with an exchangeable within-group correlation structure (the same correlation between observations). To estimate the coefficient standard errors, we apply the Huber-White sandwich estimator. To address the issue of possible nonlinearities between circularity and its drivers, we include quadratic terms in our model. Adopting such an approach is anchored in the literature on the threshold effects of eco-innovation (Sun et al., 2022) and human capital (Kijek & Kijek, 2020), as well as the Environmental Kuznets Curve with the recycling hypothesis (Kasioumi & Stengos, 2020). We use backward elimination, starting with the model with all possible predictors (Table 1) and successively removing non-significant regressors. The results of the models with logit link function and exchangeable correlation structure are presented in Table 3.

Table 2. Descriptive statistics, correlations and panel decomposition of standard deviation of variables

Variable	Min	Max	Mean	Std. dev. overall	Between	Within
CIR	1.2	30	8.75	6.31	6.15	1.80
PAT	0	11.9	0.84	1.28	1.13	0.64
GDP	46	283	100.64	43.10	43.38	6.01
EDU	0.5	6.3	2.60	0.97	0.96	0.27
TET	4.33	11.75	7.48	1.75	1.71	0.50
OAD	17.2	35.8	27.32	4.07	3.74	1.75
Correlations	CIR	PAT	GDP	EDU	TET	OAD
CIR	1					
PAT	0.237*	1				
GDP	0.296*	0.740*	1			
EDU	–0.037	–0.156*	–0.187*	1		
TET	–0.235*	–0.319*	–0.465*	0.331*	1	
OAD	0.148*	–0.205*	–0.303*	0.202*	–0.025	1

The spatial distribution of the circular use of materials and the number of patents in 2010 and 2019 are presented in Figure 1.

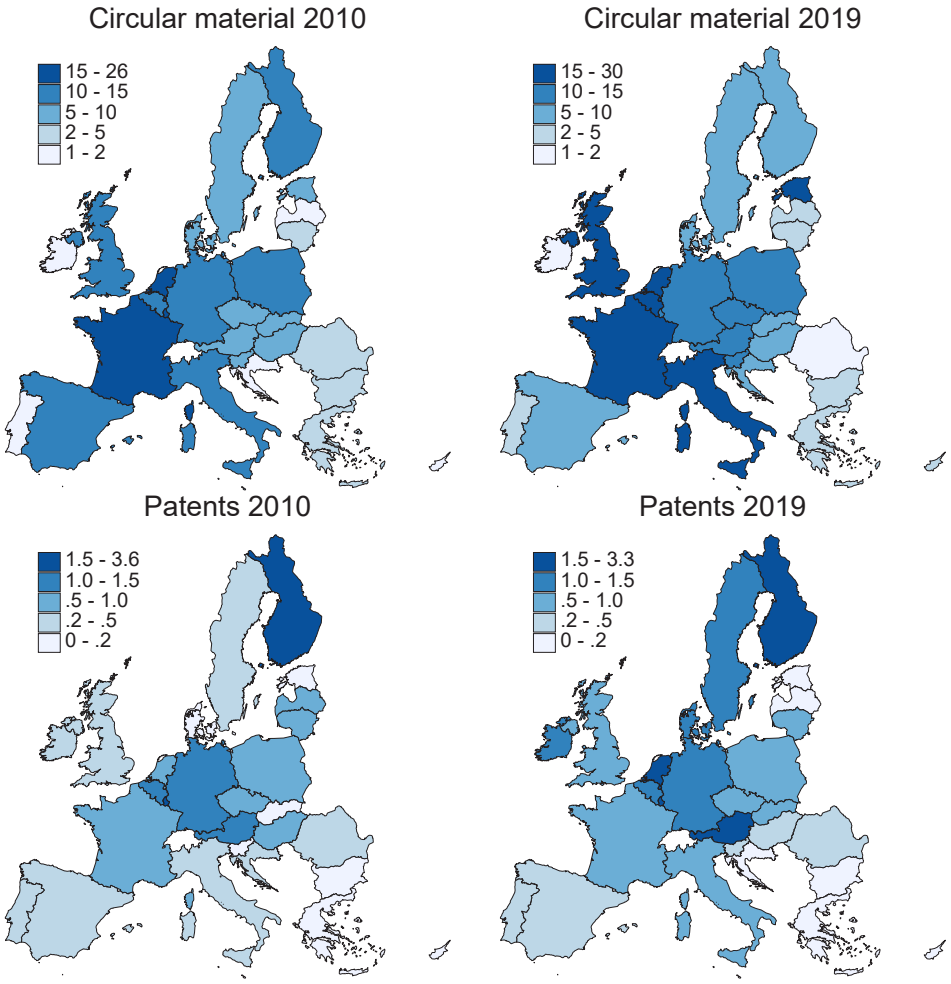

Figure 1. The spatial distribution of circular use of materials and number of patents

Table 3. Parameter estimates of GEE population-averaged model

CIR	(1)	(2)	(3)
PAT	0.021	-	−0.036
PAT^2	-	0.003***	0.005**
GDP	0.013***	0.015***	0.014***
GDP^2	−0.0001***	−0.0001***	−0.0001***
EDU	−0.447***	−0.444***	−0.433***
EDU^2	0.075**	0.075***	0.074***
cons	−2.602***	−2.721***	−2.659***
Wald chi2 (p-val)	24.01 (0.000)	102.12 (0.000)	273.48 (0.000)
QIC	132.769	132.648	132.945

Note: * p<0.10, ** p<0.05, *** p<0.01.

It can be observed that the model with patents only in quadratic form (Model 2) has the smallest QIC, and thus is chosen as the preferred model. The results show that patents have a positive and increasing impact on the circular use of materials. This finding confirms our hypothesis. Other studies also report the positive impact of eco-innovation on circularity. For example, Bao et al. (2023) study the nexus between environmental innovation and circularity in European economies. Their results show that EI-related patents have a negative impact on municipal waste per capita, which leads to an improvement in environmental quality. Contrary to our research, this study provides inconclusive findings on nonlinearity in the link between eco-innovation and circularity. The increasing returns to eco-innovation may arise from the cumulative knowledge stocks embedded in patents related to recycling and secondary raw materials. Notably, lower knowledge stocks of entrant technologies are a barrier to knowledge diffusion (Hötte, 2019). Barbieri et al. (2020) argue that green technologies protected by patents are different from non-green technologies. It is worth pointing out that green patents are more complex and provide greater knowledge spillovers, as manifested in their greater effect on subsequent technological inventions compared to non-green patents. Importantly, eco-innovation and CE targets are complementary. Since the publication of the European Union's Circular Economy Action Plan in 2015, most measures and almost all targets have increasingly focused on improving the recycling of different types of waste (Friant et al. 2021). According to Porter's hypothesis, strong regulations that limit environmental impacts force firms to engage in green innovation research and create markets for environmentally beneficial products and services (Porter & van der Linde, 1995).

Regarding the EKC with recycling, our results should be contrasted with the theoretical model developed by Pittel (2006), who shows that under certain initial conditions, preferences, and externalities arising in the recycling sector, the EKC (i.e., a hump-shaped path) for non-renewables may emerge during the transition to the long-run balanced growth path. This contradicts the argument proposed by George et al. (2015). In line with their model, environmental quality cannot be maintained or improved through economic growth. The former can be enhanced by increasing the environmental self-renewal rate or the recycling ratio. Similar to our study, Kasioumi and Thanasis (2020) examine the relationship between GDP per capita and recycling for 50 states in the United States and find an inverse U curve for the Middle Rich states.

Another factor with a nonlinear impact on the circular use of materials is human capital, measured by the EDU variable. We find that the positive effect of increasing the share of pupils and students with bachelor's degrees or equivalent levels in the total age population is triggered beyond a threshold, reflecting a critical mass of educated people. As such, we confirm the results of other studies that show a positive link between higher education levels and broader environmental consciousness of the CE (Neves & Marques, 2022), while shedding new light on a possible negative effect (Sánchez-Llorens et al., 2019). It is worth noting that our results neither corroborate nor contradict studies that point to either a positive association between age and willingness to recycle and/or waste generation (Nixon & Saphores, 2007) or a negative one (Chu et al., 2013). Finally, it emerges that total environmental tax revenues have insufficient statistical significance in explaining the circularity rate of the EU economies. This is hardly surprising, as Ha (2023) reveals the heterogeneous effects of an environmental tax on circularity and shows that circular material usage is affected the least when pollution and resource tax revenues increase.

CONCLUSION

The aim of this study is to analyze the link between eco-innovation and the circularity of EU economies. To do so, it investigates the role of patents related to recycling and secondary raw materials in the circularity rate. The empirical analysis applies annual panel data for 28 EU countries from 2010 to 2019. The three models are estimated using different specifications. The Huber-White sandwich estimator is used in all models. The main finding is that increasing gains in circularity are achieved through inventions related to recycling and secondary raw materials. This result provides a compelling rationale for prioritizing and incentivizing investments in promising technologies to achieve both environmental sustainability and economic prosperity in the long term. It should be noted that European universities and public research organizations are pioneering a range of technologies that foster reusability, recyclability, and waste recovery (EPO, 2021a). The major challenge face by many is bringing them to the market through innovative spinoffs or selling/licensing IPRs. KT Boost, a new knowledge transfer funding program for Irish universities and technological universities, is a good example of how to support knowledge transfer from universities and boost their innovative capacity and capability, whilst also supporting firms to access new knowledge and expertise, to drive innovation through collaboration, and to identify and license new technologies and IPRs (Government of Ireland 2023).

Additionally, we reveal that the relationship between the circular use of materials and GDP per capita is characterized by an inverse U curve. This means that the circularity ratio increases as the GDP increases until it reaches its highest point and then starts to fall. This may be due to several reasons. Most importantly, as GDP increases and countries grow richer, firms may invest more in circular materials to reduce environmentally harmful waste. However, as these activities become more expensive, their efficiency decreases. Therefore, new and more effective recycling methods must be developed and commercialized to overcome this problem. With respect to human capital, a critical mass of well-educated people is needed to provide and promote an effective transition to CE. In this situation, policymakers should increase the attractiveness of circular materials to consumers, particularly those with the least education.

This study has several limitations. These are mainly concerned with the sample size and ways to measure eco-innovation and its determinants. It should also be noted that due to the existing information gap (lack of some data), it was not possible to carry out regression analyses for a balanced panel of EU countries. Furthermore, because our analyses involve data for the EU countries only, for future research, some possible extensions could include data for selected OECD countries to increase confidence in the results we show in this paper. Additionally, future studies could apply different proxies for eco-innovation related to CE, such as green R&D and a broader set of other CE drivers, including both regulations and incentives.

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Conflicts of interest

The authors declare no conflict of interest.

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