Promoting circular economy in EU: how to enlarge the recycling of e-waste?

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Resumo

A transição da economia linear para a Economia Circular é crucial para reduzir a pressão nociva sobre o ambiente. Esta transição é particularmente relevante na indústria dos Equipamentos Elétricos e Eletrónicos (EEE), dado que são o fluxo de geração de resíduos com maior crescimento, a sua eliminação inadequada causa severos problemas ambientais. A reciclagem de resíduos eletrónicos é uma solução para lidar com as cada vez maiores quantidades desses resíduos e assim reduzir a dependência deste sector das matérias-primas primárias e aumentar a utilização de matérias-primas secundárias. Por conseguinte, este estudo pretende analisar o que motiva e o que prejudica a reciclagem de resíduos dos EEE, considerando os fatores económicos, sociais e ambientais. Para alcançar este objetivo, foram utilizados dados anuais de 2010 a 2018 para um painel de 20 países da União Europeia, utilizando o Método Generalizado de Momentos *Arellano-Bond*. Os principais resultados sugerem que a distribuição etária da população é significativa na explicação das taxas de reciclagem dos países. Os idosos e os jovens contribuem para reduzir a taxa de reciclagem de resíduos eletrónicos, o que poderá indicar a sua relutância em mudar o seu comportamento não sustentável. Assim, são necessárias políticas centradas nos idosos para os sensibilizar para as vantagens e importância da reciclagem e melhorar o seu acesso às instalações de reciclagem. Adicionalmente, o Produto Interno Bruto tem um impacto negativo na reciclagem, indicando que os países com maior crescimento económico podem ter um problema de consumo excessivo, levando a uma substituição dos equipamentos quando estes ainda estão perfeitamente funcionais.

Palavras-chave

Reciclagem; Resíduos eletrónicos; Ambiente; Economia Circular; União Europeia.

Resumo Alargado

O crescimento económico dos países tem tido por base um modelo de economia linear, sendo este cada vez mais dependente de recursos finitos. Este modelo de crescimento tem contribuído para um aumento da poluição, não apenas decorrente das emissões de gases poluentes, mas também da poluição dos solos e oceanos através do resíduo aí colocado. Além disso, o aumento do consumo tornou os recursos cada vez mais escassos, comprometendo assim a sua disponibilidade para gerações futuras. Deste modo, a Economia Circular (EC) surge como uma alternativa ao modelo linear, tendo por base os princípios "reduzir, reutilizar e reciclar". Neste sistema mais sustentável, a vida útil dos produtos é prolongada e a geração de resíduos reduzida. A implementação da EC é ainda um desafio para as economias, embora se tenha tornado um objetivo progressivamente presente nas agendas políticas dos países.

Na ótica de transição para uma EC, o setor dos equipamentos elétricos e eletrónicos (EEE) merece particular atenção. Por um lado, devido ao rápido desenvolvimento tecnológico, a geração de resíduos eletrónicos tem aumentado significativamente, sendo o tipo de resíduo que mais cresce. Portanto, é necessário criar formas eficientes e ambientalmente responsáveis para gerir este resíduo. Por outro lado, dada a complexidade dos componentes existentes nos EEE, o processo de reciclagem é mais difícil e dispendioso do que o de outros resíduos. Apesar dos desafios ainda existentes, os EEE têm também oportunidades associadas à sua reciclagem. Os EEE contêm componentes valiosos, que através da reciclagem poderão ser retirados e reintroduzidos no mercado, permitindo reduzir a extração desses componentes escassos da natureza, aumentando a sua vida útil. Deste modo, é imperativo aumentar a reciclagem de resíduos dos EEE, evitando que seja colocado em aterros sanitários.

Este estudo tem como principal objetivo analisar os fatores que motivam e também os que representam uma barreira à reciclagem de resíduos dos EEE. Pretende-se analisar o impacto de fatores económicos, sociais e ambientais na reciclagem de EEE. O constante e rápido desenvolvimento tecnológico torna disponíveis no mercado novas e melhoradas versões de EEE. Assim, esta dissertação contribui para a restante literatura, primeiramente, por apresentar nova evidencia empírica para o fluxo de resíduo que mais cresce. Em segundo lugar, a complexidade dos componentes dos resíduos eletrónicos dificulta o processo de reciclagem e causa graves danos ambientais quando são geridos de forma inadequada (em aterros sanitários, por exemplo). No

entanto, os componentes dos resíduos eletrónicos têm um elevado valor de mercado, e a sua reciclagem poderia reduzir a extração da natureza destas valiosas matérias-primas, o que constitui uma oportunidade que o sistema circular deve aproveitar. Em terceiro lugar, os resíduos eletrónicos não são como outros fluxos de resíduos comuns, como os resíduos sólidos urbanos, nem no processo de reciclagem nem nas informações pessoais que alguns EEE contêm. De facto, a existência dessa informação pessoal poderia funcionar como uma barreira à reciclagem, uma vez que as pessoas poderiam hesitar em entregar os seus EEE para reciclagem. Por estas razões, é crucial compreender como os decisores políticos podem intervir para promover a reciclagem de resíduos eletrónicos. Por conseguinte, mesmo com as limitações do período relativamente curto dos dados, esta investigação preenche esta lacuna através de métodos econométricos inovadores, que também testam se a taxa de reciclagem de um período é explicada pelos seus níveis passados.

A União Europeia é o objeto deste estudo por estar comprometida em promover a transição para uma EC e por ter em vigor diversas políticas com vista a alcançar esse objetivo. Dada a indisponibilidade dos dados, apenas 20 países da UE foram considerados, com dados anuais de 2010 a 2018. Como variável dependente utilizou-se a taxa de reciclagem de resíduos eletrónicos (RR). Tendo por base a literatura, pretende-se que as variáveis explicativas quantifiquem os fatores económicos, sociais e ambientais. Como fatores económicos, consideraram-se o Produto Interno Bruto per capita (GDPpc), os gastos do estado em pesquisa e desenvolvimento (GERD) e ainda a percentagem de emprego quer para o sector dos serviços (EMPS), quer para o sector da agricultura (LEMPA). Em relação aos fatores sociais, a percentagem da população em diferentes faixas etárias, dos mais jovens (POP15) e dos mais idosos (POP65), a percentagem da população com educação terciária (EDU). Os fatores ambientais incluem, as receitas das taxas ambientais (ETR), as emissões de CO2 (CO2PC) e o total dos resíduos EEE recolhidos (WCOL).

O teste de *Hausman* foi utilizado para testar a presença de efeitos fixos ou efeitos aleatórios e concluiu-se que o modelo de efeitos fixos era o mais apropriado. Posteriormente, vários testes de especificação foram realizados, nos quais se confirmou a presença de heterocedasticidade e autocorrelação de primeira ordem. Desta forma, o estimador *two-step system GMM* (Método Generalizado de Momentos) *Arellano-Bond*, foi aplicado devido à sua robustez em painéis onde o período temporal é reduzido, como é o caso (2010-2018) e ainda devido à sua robustez na presença de heterocedasticidade e autocorrelação. Com este método, é ainda possível perceber as

implicações que as taxas de reciclagem do passado têm no presente, o que é bastante pertinente dentro da temática da transição para a EC.

Os principais resultados indicam que o Produto Interno Bruto per capita e a *proxy* utilizada para investimento em pesquisa e desenvolvimento contribuem para reduzir reciclagem de EEE. Isto poderá indicar que a riqueza dos países não está a ser utilizada para melhorar as instalações de reciclagem de resíduos eletrónicos. Em relação à pesquisa e desenvolvimento, os resultados podem indicar que os países revelam mais preocupação com os problemas ambientais decorrentes das emissões do que com os problemas ambientais provenientes da gestão inadequada dos resíduos. Provou-se também que a educação contribui para aumentar as taxas de reciclagem de EEE, corroborando os resultados frequentes na literatura. Devem ser propostos objetivos ambiciosos de redução das emissões, mas também objetivos relacionados com a redução dos resíduos gerados e com o aumento das taxas de reciclagem. Os decisores políticos devem promover comportamentos ambientalmente responsáveis dos países.

Em suma, os fatores económicos, sociais e ambientais são relevantes na promoção da reciclagem de EEE. Portanto, os decisores políticos poderão delinear políticas com base nestes resultados. Por exemplo, poderão promover ações de sensibilização para a necessidade de reciclar o resíduo de EEE, recompensar os que reciclam mais e baixar os preços dos EEE reciclados. Poderão também considerar a possibilidade de existirem barreiras psicológicas à reciclagem de EEE, dado que os EEE podem conter informações pessoais relevantes. A regulação deve intervir, de modo a garantir a segurança e a confidencialidade das informações daqueles que entregam os seus equipamentos pessoais para reciclar. Adicionalmente, pode ser introduzido um imposto sobre a compra de novos EEE pelas famílias, por exemplo computadores e telemóveis, aquando da não entrega do equipamento antigo para reciclagem ou reutilização. Todas estas mudanças promovem a transição para a EC, que é necessária para a sustentabilidade ambiental.

Abstract

Evolving from a linear economy to a Circular Economy is crucial to reducing environmental pressure. This transition is particularly relevant in the Electrical and Electronic Equipment (EEE) industry. The waste from EEE, known as e-waste, is the fastest-generation waste stream, and improper disposal causes severe environmental problems. The recycling of e-waste is a solution to deal with the growing amounts of e-waste and thus, reduce the dependence of this sector on primary raw materials and increase the use of secondary raw materials. Therefore, this paper aims to analyze the drivers and barriers to e-waste recycling, considering the economic, social, and environmental factors. To achieve this, yearly data from 2010 to 2018 for a panel of 20 European Union countries were analyzed employing a Generalized Method of Moments Arellano-Bond. The main findings suggest that the population's age distribution is significant in explaining the recycling rates of the countries. The elderly and young people negatively affect e-waste recycling, which could indicate their reluctance to change their unsustainable behavior. Thus, policies focusing on the elderly are needed to make them aware of the advantages and importance of recycling and improve their access to recycling facilities. Additionally, Gross Domestic Product has a negative impact on recycling, indicating that countries with higher economic growth may have an overconsumption problem, leading to replacement of equipment when it is still perfectly functional.

Keywords

Recycling; E-waste; Environment; Circular Economy; European Union

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List of Acronyms

CD-Test	Cross Sectional Dependence Test
CE	Circular Economy
CIPS	Second Generation Unit Root Test
CO2	Carbon Dioxide
EEE	Electrical and Electronic Equipment
EEE	Equipamentos elétricos e eletrónicos
EC	Economia Circular
EPR	Extended Producer Responsibility
EU	European Union
FE	Fixed Effects
GDP	Gross Domestic Product
GDPpc	Gross Domestic Product per capita
GMM	Generalized Method of Moments
MSW	Municipal Solid Waste
PRO'S	Producer's Responsibility Organization
R&D	Research and Development
RE	Random Effects
VIF	Variance Inflation Factors

1. Introduction

The traditional linear model of material extraction-production-use-disposal is unsustainable, even though it has contributed to global economic development. As a result, the environment has suffered severe harm (Rizos & Bryhn, 2022)[1]. With this in mind, Circular Economy (CE) arose as an alternative to the linear model (Suárez-Eiroa et al., 2021). CE backed up on the imperatives "Reduce, Reuse, and Recycle" is crucial to decrease environmental damage. For that, the lifespan of the products must be enlarged, and the waste generated must be reduced. This scenario is especially relevant in Electrical and Electronic Equipment (EEE), given that there is an increasing trend in their usage and waste generated, which is not expected to change soon.

The EEE sector is a key sector where progress towards a circular transition has been limited. EEE is any equipment that depends on electric currents or electromagnetic fields to work correctly, including equipment for generating, transferring, and measuring electric currents (Babu et al., 2007). Significant quantities of still working EEE, such as mobile phones, tablets, and chargers, should be collected for recycling across the European Union (EU) (Rizos & Bryhn, 2022). Globally, Forti et al. (2020) estimate that less than 20% of e-waste generated is correctly managed according to environmental principles.

E-waste mismanagement can lead to serious environmental and health risks. Proper e-waste management is a challenge due to the global increase in e-waste, and its potential as a source of valuable resources and a cause of contamination (Dias et al., 2019). People's routines are based on the continuous use of personal computers, laptops, televisions, among others. Therefore, enormous concern develops when technology becomes obsolete or faulty (Brindhadevi et al., 2023). The real issue is that more electronic items are discarded in landfills, implying a threat to human health and the environment due to the hazardous fumes and chemicals they emit (Awasthi et al., 2018).

Looking to improve the recycling performances of the countries, the analysis of the drivers and barriers has been previously the focus of other authors to study different types of waste, such as, municipal waste (Cerqueira & Soukiazis, 2022; Soukiazis & Proença, 2020; Starr & Nicolson, 2015) or e-waste (Boubellouta & Kusch-Brandt, 2022;

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[1] This dissertation follows the 7th Edition of American Psychological Association (APA) reference style.

Bressanelli et al., 2021). However, additional empirical evidence is required given that too many factors are involved and some of them possibly unexplored sufficiently. Furthermore, the nonconsensual findings indicate that is necessary more empirical evidence. Therefore, this paper aims to contribute for that debate by exploring the drivers and barriers to the recycling rate of e-waste in EU countries. Briefly, this paper intends to answer the following central question: what are the main drivers and barriers to recycling e-waste?

EU is the case study of this paper due to the usual higher generation of e-waste compared to countries with a lower stage of economic development (Awasthi et al., 2018). Furthermore, EU policymaking is strongly committed to promoting an early transition to a CE and has implemented several policies, such as sustainable product use and Extended Producer Responsibility (EPR). In 2019, through the Green Deal, it was announced that the EPR would be strengthened with new procedures (Giannakitsidou et al., 2020). The intention to promote new business models and the inclusion of minimum requirements prevent the use of environmentally harmful products in the EU market. The increasing circularity of resource extraction and circular approaches at the product level, also offer opportunities to reduce overall environmental impacts as well as dependence on resources from other countries, which would allow the EU to be less exposed to market volatilities and shocks in the international markets (SWD, 2020).

This paper uses annual panel data from 2010 to 2018 for 20 EU countries to accomplish this objective. Given the possible dynamic nature of the relationships under analysis, the Generalized Method of Moments (GMM) proposed by Bond & Arellano (1991) was employed. The main findings indicate that the recycling of e-waste is driven by the e-waste collected, environmental taxes and education, while population age structure, R&D, Gross Domestic Product per capita (GDPpc), and both employment in primary and tertiary sectors act as a barrier.

This research contributes by analyzing drivers and barriers toward e-waste recycling based on data from a group of EU countries. The detailed novelty of this research can be expressed as follows. First, e-waste is the faster waste stream on generation, and it is not expected to change in the future. The digitalization of the economies contributes to aggravating this issue by increasing the use of EEE. Additionally, the constant and fast technological development makes new, improved versions of EEE available in the market. Second, the complexity of the components of the e-waste difficult the recycling process and cause severe environmental damage when unproperly managed (in landfills, for instance). At the same time, the components of e-waste have a high market value, and its recycling could reduce the extraction of these precious primary raw materials, which is an opportunity that circular system must take advantage. Third, the e-waste is not like other common waste streams, like MSW, neither in the recycling process nor in the personal information that some EEE contain. In fact, the existence of that information could act as a barrier for recycling, as people could be hesitant to deliver their EEE for recycling. For those reasons, it is crucial to understand how policymakers can intervene to promote the recycling of e-waste. Therefore, even with the limitations of the relatively short time span of the data, this paper fills this gap by innovatively using econometric methods, which also test if the recycling rate of a period is explained by its past levels.

The rest of this paper consists of: Section 2 comprehensively elucidates the literature related to the topic and a brief overview of the factors related to recycling rate and waste generation of different waste streams; Section 3 presents the data used and the methodology applied. Results are displayed in Section 4. Discussion and recommendations in Section 5. Section 6 presents the main conclusions.

2. Literature Review

The EEE is considered an essential component of the daily routine worldwide (Boubellouta & Kusch-Brandt, 2021; Kumar et al., 2021). The production of EEE has grown, and the global amounts of e-waste[2] will change as economies grow and new technologies are developed. In some countries, the total number of computers and other potential e-waste items is correlated with their GDP since EEE is essential for the economies (Boubellouta & Kusch-Brandt, 2021; Kumar et al., 2021; Robinson, 2009).

The EEE is in constant technological upgrading, and consumers tend to prefer to keep up with recent innovations. This overconsumption makes the older equipment e-waste, even if it is perfectly functioning. The mismanagement of this e-waste causes the release of its chemical composition into the environment, impacting the entire ecosystem, including humans. As the fastest-growing waste stream, adequate waste management is a priority of the political agenda (Kumar et al., 2021). Proper collection and recycling of e-waste allow the recovery of reusable components, like precious

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[2] Waste represents general waste, including e-waste and MSW; e-waste represents electric and electronic waste; MSW represents Municipal Solid Waste.

metals, especially copper. To promote this, countries and organizations have drafted national legislation to improve the reuse, recycling, and other forms of material recovery from e-waste, aiming to reduce the waste in landfills (Babu et al., 2007).

Policies and legislations were proposed and implemented as long as environmental concerns grew. For instance, EPR and Waste Hierarchy are policy instruments introduced in the EU. EPR is an environmental policy in which a producer's responsibility for a product is expanded to the post-consumer phase of a product life cycle (Compagnoni, 2022). EU countries were the pioneers in implementing EPR, which enhances the circularity of the value chains affected by this regulation, it also hampers the ability to assess the policy impacts alignment with CE objectives (Compagnoni, 2022).

The Waste Hierarchy was announced in the waste framework directive, where according to Article 4 a hierarchy shall apply as a priority order in waste prevention and management legislation and policy (The European Commission, 2008). The Waste Hierarchy supports that if waste is treated in the established hierarchy, landfill material deposits could be avoided, and the reutilization of materials could be higher, promoting the transition to CE and benefiting waste management (Stoeva & Alriksson, 2017). While the Waste Hierarchy legislation incentives producers to minimize the waste generated, the EPR schemes strive to activate all stakeholders throughout the product life cycle, i.e, Producer's Responsibility Organizations (PROs), that go from national authorities to the recycling industries (Pouikli, 2020).

Several benefits for the current societies could come from CE, namely environmental, economic and social. Environmental improvements could arise by reducing the consumption of resources (Bressanelli et al., 2021) and waste disposed of and unproperly managed. Furthermore, CO2 emissions could be significantly reduced if the economies are based on renewable energy and resource efficiency (Skanberg et al., 2014). The economic advantages could come from the increased efficiency towards the management of products and goods, also enable sustainable economic development (Prieto-Sandoval et al., 2018), furthermore, Andersen (2007) concluded that the economic costs of environmental externalities support a more circular economy. Finally, the potential job creation and easier access to products can enhance life quality (Bressanelli et al., 2021) and provide social benefits. To achieve this, the linear economy must be replaced by the CE. The 3R's imperatives of Reduce, Reuse and Recycle, are recognized as the starting point for more sustainable development and for a CE (Reike et al., 2018). Priority should be provided to the reduction of consumption and waste generation (Reike et al., 2018). The literature found that economic, social and environmental factors are significantly related to the countries' recycling rate and/or waste generation considering different waste streams and/or geographical locations (Bressanelli et al., 2021; Ghisellini et al., 2016; Hina et al., 2022; Rizos & Bryhn, 2022). The following subsections describe this literature.

2.1. Economic Factors

The circular economic system could drive economic growth towards sustainability, shifting goods' production and consumption towards maximizing the productivity of resources and energy while avoiding environmental degradation (Lehmann et al., 2022). The relationship between GDP and CE is controversial due to the non-consensus established by various authors.

On the one hand, some studies show that waste generation increases along with economic growth. For instance Awasthi et al. 2018 and Xavier et al. (2021) results show that economic growth depends on waste generation. Additionally, Boubellouta & Kusch-Brandt (2022) found that e-waste recycling rate increases with economic growth. Boubellouta & Kusch-Brandt (2021) found a non-linear relationship between economic growth and mismanaged e-waste (proxy of environmental damage), forming an inverted U-shape. In that case, during the early stage of economic growth, the mismanaged e-waste increases with economic growth, but after attaining a certain GDP level, known as the turning point, the mismanaged e-waste decreases as long as GDP increases.

On the other hand, several authors achieved negative impact Önder (2018) found that GDP has a negative effect on the recycling rate of a country. Similarly, (Lehmann et al., 2022) established that GDP effect on circularity is negative, while environmental degradation is positively affected. Circularity is a trustworthy indicator that measures the share of secondary raw materials that are reintroduced in the economy, this indicator acts as proxy for resource circularity (Kumar et al., 2021). Also, Neves & Marques (2022) results indicate that higher income can cause less material circularity, proving that wealthiness provokes a higher desire to buy new items instead of products conceived through recycled materials or the reutilization of the products.

The current rapid technological advances cause larger amounts of e-waste, the increased production of EEE rapidly turns to e-waste when the end of its useful life is reached. To control this, efficient strategies are needed, both at the production stage and after use for a proper management of e-waste. Recycling is a valuable instrument for monitoring emerging e-waste (Ahirwar & Tripathi, 2021). A possible solution to the above-mentioned waste mismanagement is investing in R&D. Investing in R&D allows technological development that can be a driver of change in markets, such as the reutilization of products, more efficient material recovery or the use of recovered materials in different industries (Rizos & Bryhn, 2022). The enhancement of R&D stimulates lower carbon emissions for countries and mitigates worldwide climate change. Moreover, the countries' economies can also be improved when the R&D rate increases (Gu & Wang, 2018).

The behavior of the countries on recycling and waste generation could depend on its production structure. The literature has already tested these dimensions on their empirical approach, but the results are controversial. While there is evidence supporting the idea that the primary sector drives the recycling rates of MSW while the tertiary sector decreases it (Cerqueira & Soukiazis, 2022). Thus, Önder (2018) found that the gross value added by agriculture reduces the recycling rate of packing waste. According to (Boubellouta & Kusch-Brandt, 2021), in big cities where the most productive and densely populated areas are commonly found, it is expected that the tertiary sector of the economy grows, being this sector known for making use of a considerable amount of EEE that will become e-waste.

2.2. Social Factors

Besides the economic factors, the literature has also been focused on the effect of some social factors on recycling and/or waste generation. In this sense, the effects of the age structure of the country's population have merited some attention. For instance, Lakhan (2014) and Starr & Nicolson (2015) used median age to explore the relationship between population age structure and MSW recycling rate and found that an increase in the average age implies a positive effect in the MSW recycling rate. Later on, Cerqueira & Soukiazis (2022) and Kinnaman & Fullerton (2000) discovered that the elderly tend to recycle more than the population in active age. Besides this, Kinnaman (2005) found that the younger and elderly positively affect the household recycling rate. On the contrary, Romano et al. (2019) found that age has an insignificant effect on

the recycling rate, which is a different result from the mentioned above, proving the population age structure disparities. Additionally, Lehmann et al. (2022) found no evidence that an increase in human capital positively affects CE levels.
Additionally, education has also been a social factor considered by the literature. For instance Knickmeyer (2020) and Önder (2018) results demonstrate that higher education levels positively affect the recycling rate of waste. Both authors believe that educational skills are necessary to develop the waste management process. Educational programs encouraging children to recycle early can be effective, given that children could take their school habits home and educate their parents (Knickmeyer, 2020).

2.3. Environmental Factors

The lack of awareness, environmental legislation, and financial resources could intensify challenges in e-waste management. Proper disposal of e-waste requires training and investment in recycling and management technology (North et al., 2022). To create more recycling habits and incentive population environmental awareness, the literature supports the implementation of environmental taxes (Doğan et al., 2022; Fang et al., 2022; Sousa et al., 2018). According to Sousa et al. (2018) these taxes encourage greener habits and control overconsumption. Also, Marques & Teixeira (2022) found that environmental taxes drive the reintroduction of recycled materials in the economy.

The literature finds that taxes are relevant in controlling environmental damage from energy. For instance Doğan et al. (2022) argued that more environmental taxes could lead to energy savings and consequently reduced emissions, ending in a more sustainable path. This point of view is also supported by Fang et al. (2022) results, where introducing environmental taxes increases the adoption of renewable energies and reduces CO2 emissions. The European Commission established policies to reduce CO2 emissions, where countries agreed to responsibly reduce emissions by 55% by 2030, decrease energy consumption by 25% and the imposition of CO2 emissions limits for new vehicles (European Commission, 2020).

3. Data and Methodology

This paper uses annual data from 2010 to 2018 for 20 European Union countries. The EU countries are particularly relevant given that they are pioneers in promoting CE, specifically in improving recycling performances. The data availability conditioned the use of all EU countries. Therefore, 20 EU were selected, and they are: Austria, Belgium, Bulgaria, Denmark, Czech Republic, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, the Netherlands, Slovak Republic, Slovenia, Spain, and Sweden. Table 1 shows the variables used, their description, and data sources. Table 2 reflects the descriptive statistics of the variables enunciated in the first table.

Table 1: Description of the variables and their sources

Variables	Description	Source
LRR	The recycling rate of WEEE (% of collected WEEE that is reused)	Eurostat
LWCOL	All WEEE collected and treated; (Kg/per capita)	Eurostat
LGDPPC	Gross Domestic Product per capita (constant dollar 2015 = 100) ($/per capita)	World Bank
LGERD	Gross domestic expenditures on research and development (R&D). (% of GDP)	Eurostat
LETR	Total environmental tax revenues (million €) 2015 = 100.	Eurostat
LPOP65	Population aged 65 and above. (% of the total population)	World Bank
LPOP15	Population between the ages 0 to 14 as a percentage of the total population. (% of the total population)	World Bank
LEMPS	Employment in services. (% of total employment)	ILOSTAT
LEMPA	Employment in agriculture. (% of total employment)	ILOSTAT
LEDU	The proportion of the population with tertiary education (level 5–8).	Eurostat
LCO2PC	Total CO2 emissions. (Kg of CO2 equivalent/per capita)	World Bank

Notes: all the variables were converted into their natural logarithms. The prefix "L" means a natural logarithm.

Given that the main objective of this paper is to analyze the drivers and barriers to e-waste recycling, the e-waste recycling rate (*LRR)* was used as the dependent variable. Starr & Nicolson (2015) followed a similar approach and used the residential recycling rate as a dependent variable to ascertain the main factors supporting recycling. Also, Cerqueira & Soukiazis (2022) studied the socio-economic and political factors that affect the recycling rate of municipal waste in Portuguese municipalities. Likewise, Önder (2018) used a similar approach and examined the socio-economic factors that drive the recycling rate of waste in the European Economic Area.

Inspired by the literature, this paper considers the role played by economic, social, and environmental factors on the recycling rate of e-waste. Concerning the economic factors, this paper uses GDP per capita as an economic growth proxy such as Nguyen et al. (2022). GDP could also be used as an income proxy such as Diacon & Maha (2015).

The pertinence of GDP per capita to explain recycling rates (Cerqueira et al., 2021; Önder, 2018) and waste generation (Awasthi et al., 2018; Xavier et al., 2021) is evidenced by the scientific community.

Furthermore, countries that invest more in R&D, usually the ones with higher GDP, are more likely to possess higher rates of recycling, provoked by the R&D exposure to new knowledge, adoption of clean energy, advanced products, efficient techniques, and improved methods (Rizos & Bryhn, 2022; Shahzadi et al., 2021). Additionally, the evolution of R&D and innovation has become the main interest in achieving sustainable development (Shahzadi et al., 2021). For those reasons, this paper uses gross domestic expenditures on R&D (*LGERD*) to capture the R&D effect on the recycling process of e-waste.

The production structure of the countries could have an impact on the recycling rate of e-waste. As found by Soukiazis & Proença (2020) the primary sector enlarges the recycling rate of MSW, while the secondary sector hampers it, and the tertiary sector is insignificant. These findings obtained by Cerqueira et al. (2021) corroborated the idea that the production structure of the countries may be important when the recycling performance of e-waste is estimated. For those reasons, the employment rate in the services sector (*LEMPS*) and agriculture sector (*LEMPA*) are used to capture these dimensions.

Concerning social factors, education levels could be relevant in explaining the recycling rate of e-waste. Actually, if people who possess higher educational standards are more aware and able to understand and adopt recycling habits due to consumers' awareness on environmental preservation (Knickmeyer, 2020). The human capital skills, measured by tertiary education, drive recycling rate and renewable energy (Knäble et al., 2022). Higher human capital skills are necessary for developing alternative productive processes friendlier to the environment, and recycling is an important practice to achieve that goal. Therefore, this paper uses the percentage of the population with tertiary education (*LEDU*).

Still, on the social factors, the age structure could be relevant in explaining the recycling behaviors, even with no consensus on the findings. For instance Soukiazis & Proença (2020) has proven that the population aged between 15 and 64 years is not relevant in explaining the recycling rate of MSW while older people drive it. In accordance with Romano et al. (2019) the elderly have more time to dedicate to recycling activities, however, these age groups are often limited in terms of mobility, so the older ones tend to give up recycling. The lack of consensus indicates that is required more empirical evidence. This paper contributes to it by considering the role played by the percentage of the population belonging to the oldest age group (*LPOP65*) and youngest (*LPOP15*) on recycling e-waste.

On the environmental dimension, EU countries use environmental taxes (*LETR*) to incentivize environmental protection. In the energy sector, environmental taxes policy could drive pollutant enterprises to be environmentally aware to avoid the adverse effects of fossil energies, and enterprises are more likely to choose renewable energy to produce and enhance environmental quality (Fang et al., 2022). According to Doğan et al. (2022) governments could use taxes as a direct tool to control carbon emissions. Furthermore, the relationship between environmental taxes and CE and/or recycling rates and the connection between environmental taxes and sustainable development was previously studied by Sousa et al. (2018). Given that a possible relationship between environmental taxes levels and the demand for EEE exists (Sousa et al., 2018), is there also a relationship between environmental taxes and the recycling of e-waste? Besides this, Marques & Teixeira (2022) results demonstrate that these taxes act as driver for the circularization of materials, causing a higher reintroduction of recycled materials back in the country's economy.

Table 2 Statistics descriptive of the variables

Variable	Obs	Mean	Std. Dev.	Min	Max
LWCOL	180	1.964903	0.478853	0.7129498	2.927989
LEMPS	180	4.258851	0.1064224	4.070052	4.475631
LEMPA	180	1.301876	0.6478286	-0.0100503	2.616666
LGERD	180	0.4738742	0.5374641	-0.8209805	1.311032
LGDPPC	180	10.22334	0.664447	8.768389	11.59273
LPOP65	180	2.875693	0.1405718	2.398794	3.07827
LCO2PC	180	8.850811	0.3985269	8.171319	9.990427
LPOP15	180	2.756196	0.1094346	2.581499	3.085239
LRR	180	3.606925	0.3291515	2.674149	4.655863
LCO2PC	180	8.850811	0.3985269	8.171319	9.990427
LEDU	180	3.308403	0.234533	2.674149	3.701302

Preliminary tests on the variables were carried out, namely, the Variance Inflation Factor (VIF), correlation matrix, cross-sectional dependence, and unit root test. VIF ascertain the existence of multicollinearity among the independent variables in a multiple regression model. Avoiding multicollinearity is crucial since it reduces the model's explanatory power and the independent variables' statistical significance.

The results of VIF disclosed in Table 3 show no evidence of multicollinearity. Furthermore, the correlation matrix was analyzed to describe the correlation between all the possible pairs of values in the analysis. The correlation matrix shows no evidence of collinearity in the models (see Table A.1, in appendices).

Table 3 Variance Inflation Factors (VIF)

	VIF	
Variable	MODEL I (A)	MODEL I (B)
LGDPPC	3.65	4.57
LWCOL	2.81	3.15
LPOP15	-	3.76
LGERD	2.36	2.94
LPOP65	-	2.89
LEDU	1.58	2.47
LEMPA	1.37	-
LCO2PC	1.38	1.59
LETR	1.44	1.53
LEMPS	1.34	-
Mean VIF	1.99	2.86

Cross-sectional dependence was tested under the null hypothesis of no existence of cross-sectional dependence. The results in Table 4 demonstrate that the null hypothesis is rejected for all the variables, indicating the presence of cross-sectional dependence. The second-generation unit roots test (CIPS) was performed on all the variables that revealed cross-sectional dependence. In fact, the CIPS unit root test is robust in the presence of cross-sectional dependence. The null hypothesis of the CIPS test indicates that the series contains a unit root.

As shown in Table 4, the null hypothesis is rejected for six of eleven variables supporting the stationarity of these six variables. Although this test does not provide unequivocal evidence of the stationarity for all the variables considered, according to Karlsson & Lothgren (2000), small-T panels exhibit a potential risk that the whole panel may be mistakenly modelled as non-stationary due to the low power of the tests for large proportions of stationary series in the panel. Consequently, researchers should be careful when imposing stationary or non-stationary homogeneity properties of the panel cross-sections built exclusively on the results of panel unit root tests (Karlsson & Lothgren, 2000).

Table 4 Cross sectional dependence test (CD-test) and CIPS Unit root tests

	CD-Test	CIPS
Variable		Without trend
LRR	20.92***	-2.531***
LWCOL	18.38***	-6.890***
LPOP15	-1.88*	0.876
LPOP65	39.99***	-5.627***
LETR	3.11***	0.420
LGERD	2.59***	1.108
LGDPPC	30.49***	-7.349***
LEMPS	-2.13**	0.925
LEMPA	-2.07**	-1.329*
LEDU	36.76***	1.288
LCO2PC	24.57***	1.657**

Notes: ***, **, and * denote statistical significance at 1%, 5%, and 10% level, respectively.

Remembering that the main objective is to ascertain the drivers of e-waste recycling, one model was estimated by using two different specifications A and B. The option of including different structures is explained as follows. First, it is intended to preserve degrees of freedom, especially in a small-time dimension panel. Second, for the appropriate model estimation, the number of instruments should be smaller than the number of crosses. By increasing the number of independent variables, the number of instruments also increases, which would violate this requirement. Both structures contain a common group of independent variables: *LGDPpc, LWCOL, LEDU, LETR, LGERD,* and *LCO2pc*. These variables provide a good explicative power to the models. Besides that, the model I structure (A) also includes the *LEMPS* and *LEMPA* (economic factors), and model I structure (B) includes *LPOP65* and *LPOP15* (social factors). Table 5 summarizes the independent variables used in each model.

Table 5: Description of the models

Model	Independent variables
Model I - Recycling rate of e-waste *(A)*	*LGDPpc, LWCOL, LEDU, LETR, LGERD, LCO2pc, LEMPS, LEMPA*
Model I - Recycling rate of e-waste *(B)*	*LGDPpc, LWCOL, LEDU, LETR, LGERD, LCO2pc, LPOP65, LPOP15*

The empirical analysis through panel data requires robust estimators for individual-specific variation effects. Thus, the Hausman test (Hausman, 1978) was used to verify the existence of fixed effect (FE) or random effects (RE). The results in Table 6 show that the null hypothesis of the adequacy of the random effects model is rejected, indicating that the FE estimator would be suitable for both models. Additionally, several specification tests were performed to ascertain the main features of the data and use the appropriate estimator.

In the case of the FE, the presence of heteroscedasticity can be tested using the Wald test, under the null hypothesis of Homoscedasticity. According to table 6 results, the null hypothesis is rejected in both models, confirming the presence of heterocedasticity. Additionally, the cross-sectional dependence test of Pesaran were carried out. The results of the Pesaran cross-sectional dependence test reject the null hypothesis, therefore there was evidence of cross-sectional dependence on both models. Also, the first-order serial correlation Wooldridge test for autocorrelation was employed. Autocorrelation can lead the coefficients errors to be smaller than they actually are, causing an R^2 higher than it actually is. The Wooldridge's test for autocorrelation in panel data was employed to test the presence of first-order serial correlation. The test's null hypothesis is: there is no first-order serial correlation. The results are disclosed in Table 6, proving the existence of first-order serial correlation, given that the null hypothesis is rejected.

Table 6: Specification Tests

	Model I (A)	Model I (B)
Hausman Test	34.69***	93.55***
Wald Test	473.75***	651.63***
Wooldridge Test	20.530***	19.162***
Pesaran Test	3.927***	4.320***

Notes: ***, **, *denotes statistical significance at 1, 5 and 10% levels

The literature argues that the CE level in an economy could depend on past levels (Lehmann et al., 2022), and the same occurs in MSW recycling (Cerqueira & Soukiazis, 2022). Therefore, the dynamic panel model, including a lagged dependent as an explanatory variable, is used to accomplish this paper's objective. It allows to test the persistency of the effect, i.e., if the level of e-waste recycling rate is significantly dependent from its past levels. The possibility of including the lagged dependent variable is introduced by Bond & Arellano (1991) through GMM difference estimation, wherein the endogeneity problems are surpassed. However, problems of biased coefficients in small time samples could arise on the difference GMM caused by weakened instruments. This limitation led to the creation of the System GMM, later proposed by (Blundell & Bond, 1998).

The system GMM presents the lowest bias and highest precision when the T dimension in the panel (in this case, the number of years) is small, and the series are moderately or highly persistent. Furthermore, these estimators show more efficiency than instrumental variables estimators in the presence of heteroskedasticity and have shown upgrades in small-sample properties, which is the case of this study that uses data from 9 years (2010-2018). To perform the GMM method in both of the previously stated approaches, two variants were introduced by Bond & Arellano (1991), the one-step and the two-step. The two-step is more efficient and robust in the presence of heteroscedasticity and autocorrelation (Trujillo-Baute et al., 2018).

Therefore, the two-step System-GMM method with robust errors was performed, where the instruments are the first differences of the exogenous variables and the lags of the endogenous variables. The two-step procedure provides reliable estimations in the presence of heteroskedasticity and autocorrelation. The functional form of the two-step system-GMM can be described as follows:

MODEL I – Recycling rate of e-waste (A)

$$\begin{aligned} LRR_{it} = {} & \alpha_0 + \alpha_1 LRR_{i;t-1} + \alpha_2\, LWCOL_{i;t} + \alpha_3\, LEDU_{i;t} + \alpha_4\, LETR_{i;t} + \alpha_5 LGERD_{i;t} \\ & + \alpha_6 LCO2_{pc_{i;t}} + \alpha_7\, LGDP_{PC\,i;t} + \alpha_8\, LEMPS_{i;t} + \alpha_9 LEMPA_{i;t} + \lambda_{i;t} \end{aligned} \tag{1}$$

MODEL I – Recycling rate of e-waste (B)

$$\begin{aligned} LRR_{it} = {} & \gamma_0 + \gamma_1 LRR_{i;t-1} + \gamma_2\, LWCOL_{i;t} + \gamma_3 LEDU_{i;t} + \gamma_4 LETR_{i;t} + \gamma_5 LGERD_{i;t} \\ & + \gamma_6\, LCO2_{pc_{i;t}} + \gamma_7 LGDP_{pc_{i;t}} + \gamma_8\, LPOP65_{i;t} + \gamma_9\, LPOP15_{i;t} + \varepsilon_{it} \end{aligned} \tag{2}$$

Where, α_0 and γ_0 denotes the intercept; $\alpha_i, \gamma_i, (i = 1, \dots, 9)$ denotes the coefficients of the variables. ε_{it} *and* λ_{it} denotes the error term. For i=1,..., 20 and t =2010,..., 2018.

To guarantee the consistency of the estimations, diagnostic tests must be conducted. To test over-identifying restrictions, where the instruments as a group appear exogenously (Roodman, 2009), either Sargan, Hansen J statistics or both are used. However, Hansen J-statistic is used for robust one-step and two-step estimations, while Sargan test is more efficient in one-step and non-robust estimations (OSENI, 2016). Based on this principle, this study uses the Hansen J-statistic to test the over-identifying restrictions (OSENI, 2016), testing the validity of the instruments under the non-existence of autocorrelation between the instruments and error terms. The first-order (AR1) and second-order autocorrelation (AR2) tests examine first-order and second-order serial correlations in first differenced error terms. The Difference GMM and System GMM are consistent in the absence of second-order serial correlation in the error terms of the first differenced equations (Zarra-Nezhad et al., 2014). The rejection of the null hypothesis in AR(1) supports that dynamic specification is appropriate.

4. Results

To accomplish this paper's objective, one model was estimated using different specifications, namely structure A and structure B (see section 3). Model I (A) and Model I (B) aim to assess the drivers and/or barriers to the recycling rate of e-waste and are disclosed in Table 7. These models' estimations include Hansen's statistics due to its higher performance in evaluating the validity of the instruments in the two-step system GMM estimation (OSENI, 2016). The Hansen J-statistic test of overidentifying restrictions does not reject the null hypothesis (the instruments are valid) at any conventional level of significance. Furthermore, the null hypothesis of AR(1) is rejected, and AR(2) is not rejected, indicating the correct specification of the estimated model and the adequacy of the dynamic model. Furthermore, it should also be highlighted that the number of instruments used is smaller than the number of crosses (countries in this case), which is crucial for appropriately estimating dynamic models (OSENI, 2016).

Table 7: Estimations results

	Model I *Recycling of e-waste (A)*	Model I *Recycling of e-waste (B)*
LRR(-1)	0.6831462 ***	0.6527953 ***
LWCOL	0.2871894***	0.3536558***
LPOP15		-0.6447062***
LPOP65		-0.3695375***
LETR	0.0456823	0.0953578***
LGERD	-0.1067497***	-0.0899015***
LGDPPC	-0.1136292 ***	-0.1226965 ***
LEMPS	0.1521626**	
LEMPA	0.0055087	
LEDU	0.0052933	0.1592913 ***
LCO2PC	-0.0174522	-0.0593604**
CONS	1.235899**	4.560844***
Observations	160	160
Instruments	17	17
Countries	20	20
AR(1)	-2.61***	-2.63***
AR(2)	-1.07	-1.11
Hansen Test	8.97	8.85

Notes: ***, **, *denotes statistical significance at 1, 5 and 10% levels.

From the estimated two-step system GMM models, the lagged dependent variable is significant at 1%. The high statistical significance in both estimated models is additional proof of the adequacy of the method. It means that the recycling process depends on the previous levels, showing an interannual dependency. Regarding the economic factors, GDPpc negatively affects the recycling rate of e-waste in both models. It is quite an unexpected result that deserves further attention and explanation in the discussion section.

One of the main mechanisms that could decouple economic growth from environmental damage is R&D investments in environmental protection. However, this paper founds that the *LGERD*, i.e, investing in R&D is reducing the e-waste recycling, indicating that R&D could not being used to support the recycling of e-waste. Given the coverage of the variable used (comprises the total expenditure on R&D by resident enterprises, research institutes, universities, government, etc...) it could indicate that the R&D could be significant for the creation of new EEE, and therefore increase the amount of e-waste that apparently the recycling system is not able to receive. This outcome also deserves further attention in the discussion section.

Additionally, the EU country's production structure was included. The results show that the tertiary sector (*LEMPS*), services, has a positive impact on the recycling rate of e-waste, thus, it is more helpful towards increasing the recycling rate of EEE than the industrial sector. Meanwhile, the primary (*LEMPA*) does not show any statistically significant effect. Besides this, CO2 emissions per capita, negatively affect the recycling rate of e-waste. It shows that countries are highly dependent on emissions and, therefore, are less environmentally involved and, consequently, could also be less concerned about improving the recycling rates of e-waste. On the contrary, environmental taxes revenues contribute to an increase in the recycling rate of e-waste in model I (B), but it is not significant in Model I (A).

Regarding social factors, from Model I (B), one can see that high education levels (*LEDU*), positively affect the recycling rate of e-waste. With respect to population age distribution, in Model I (A), it seems that both older and younger people are not concerned with transitioning to a CE by increasing the e-waste recycling levels. The estimations result from model I (B) show that older and younger population groups are less likely to promote the recycling of e-waste than people in active age (15-64 years old). Our results confirm the studies provided by Soukiazis & Proença (2020), where the younger harmed the recycling rate of MSW waste.

5. Discussion and Recommendations

Pursuing to contribute to the literature on the transition to the Circular Economy, specifically on e-waste recycling, the role played by social, economic, and environmental factors was studied. Since the countries in the study belong to the EU, it is essential to remark that the European Union Commission is taking several measures. The European green deal was announced in 2019, and several key measures were proposed to State Members, such as, a repair policy including the right to update obsolete software, regulatory measures on EEE chargers, improved e-waste collection for mobile phones, tablets and chargers, lastly, rules on hazardous substances in EEE. This common policy guideline justifies the existence of fixed effects in the models of this paper. Furthermore, this study shows that new policies should be included considering the economic, social and environmental dimensions.

Considering the economic factors, this paper shows that higher GDPpc is reducing the recycling of e-waste. This unexpected effect deserves further of our attention. In fact, as argued by Diacon & Maha (2015), income level is relevant to increase the consumption level of goods and services. Higher consumption levels could lead to a higher economic capacity to substitute functional equipment for new ones, which results in an enlargement of the e-waste generation. One possible explanation for the negative effect of GDP on e-waste recycling could be that the countries' wealth is not being used to improve the e-waste recycling facilities. Still, it could indicate that the GDP per capita is not used to promote recycling. From a different point of view, it could indicate that higher incomes, lead to higher consumption of EEE, and the recycling system is not capacitated to deal with when it becomes e-waste. Policymakers should invest in creating e-waste recycling facilities and enlarge the available collection points for e-waste. In addition, policies that promote changes in industries more dependent on pollution, for example, encouraging the use of recycled materials, allowing lower taxes as a premium to industries that prove more investment in greener products.

According to the literature, wealthier countries tend to invest in R&D, but this paper's results deny that these investments are directed to the recycling system. This paper finds that R&D expenditures are a barrier to recycling e-waste. There are at least two possible reasons for that. On the one hand, it could indicate that the countries are more concerned about the environmental problems from emissions than the environmental problems from poorly managed waste. The recent EU policymaking prioritize waste management and recycling, and the countries must invest in R&D to improve the recycling process. In that way, the negative effect of economic growth on e-waste recycling could be reverted. On the other hand, R&D investments could promote innovations in the EEE, making EEE more attractive to consumers.

These consumers substitute older EEE for its improved versions and could not be incentivized to recycle the old ones. Some EEE, like computers, smartphones, and smartwatches, contain relevant personal information (addresses, bank accounts data, routines...). The share of these information could compromise consumers' security. Therefore, consumers could be hesitant to deliver old EEE for recycling with personal information, which could be a psychological barrier to recycling. Must be demanded additional regulation towards the delivery of old EEE for recycling, for instance, the receivers of old equipment should be obliged to delete or remove the disk containing the information, informing the consumers of that.

Regarding the impact of social factors, high education levels play an important role. An earlier educational approach to environmental concerns and circular economy benefits should be considered by the countries. These results corroborate those obtained by

Knäble et al. (2022), Knickmeyer (2020), Önder (2018) and Soukiazis & Proença (2020), where a positive effect on the recycling rate was expected when the share of tertiary education level was higher. Therefore, higher human capital skills are needed to create alternative processes friendlier to the environment, such as recycling. Policymakers should continue to invest in education to promote an environmentally friendly lifestyle. Also, higher education levels might lead to innovations that can help to solve global environmental problems (Ajibade & Boateng, 2021).

The negative effect in the group age categories shows that policymakers should assist the population in general, both younger and older generations to increase their recycling habits, for instance, place more recycling collection points close to the population to help the elderly with physical challenges, one of the barriers pointed out by the literature (Cerqueira & Soukiazis, 2022). On the one hand, the policy of return of the old equipment when buying the new one for posterior recycling or reuse should be further incentivized by policymaking. This delivery of old equipment should be further regulated, namely personal data protection, such as previously mentioned. On the other hand, the rewards or even encouraging the population to buy recycled materials by lowering its prices, could create an important driver to the recycling of e-waste. For young people, policymakers should use advertising measures, use toys and cartoons in an educational way and in accordance with the circular economy principles. Also, if children were incentivized to recycle at school, it would become routine, and this knowledge will spread to the other family members.

Concerning the environmental factors, this paper finds that environmental taxes are increasing the recycling rate of e-waste. Eventually, taxes for sellers of EEE who do not return old equipment for recycling could effectively promote e-waste recycling. Also, the consumers should be incentivized to return the old EEE when buying a new one through, for instance, discounts on the new EEE. Another way could be promoting the application of these taxes for private consumers who buy a new EEE without delivering their old equipment for reuse or recycling. Meanwhile, CO2 emissions are associated to lower recycling levels of e-waste. It implies that countries that are more dependent on emissions could also be less concerned about improving the recycling rates of e-waste. Ambitious goals should be proposed containing not only the emissions reduction target but also goals related to reducing waste generated and increasing the recycling rates. The EU policymaking should be rigid with the environmentally responsible behaviors of the countries.

In sum, wealth and innovation should be channeled towards environmental performance improvement. For instance, upgrading recycling facilities and improving the EEE life cycle could be attained. These changes could make a difference in transiting for a CE. Socially, improving education and sensibilization of the population, as well as, rewarding the ones that recycle more and lowering recycled EEE prices could be a successful way to guarantee a higher recycling rate of e-waste. To conclude, the idea of promoting taxes to consumers who buy new EEE and do not return their old equipment for recycling or reutilization, could be vital to upgrade the CE and have a huge impact on environmental prosperity.

6. Conclusion

This paper aims to analyze the drivers and barriers to recycling e-waste. To do so, it evaluated the role of economic, social, and environmental factors on recycling e-waste. An empirical analysis used annual panel data for 20 EU countries from 2010 to 2018. Two models were estimated with different structures to ensure the robustness of their results, given the relatively short time span of the study data. The GMM Arellano-Bond estimator was performed in both models. This estimator was suitable to the features of the data in the study, especially the short period of time when compared to the number of countries. The conclusions are fundamental to include new policy guidelines to promote increasing recycling and reutilization of EEE. This paper confirms the importance of the economic, social, and environmental factors for transition to a CE, providing useful insights for the scientific community and policymakers to increase the populations' awareness of the environment.

Policymakers should increase the attractiveness of recycling, particularly among the least qualified and wealthy people. People answer to incentives, so fiscal policy should provide incentives to improve circularization. The main findings indicate that a country's ability to invest in R&D does not imply that this investment is used to increase the recycling rate. Regarding the impact of GDP per capita on the recycling rate of e-waste proved to be negative. Therefore, a higher GDP can promote consumption, increasing waste generation and consequently decreasing the recycling rate. At the level of social factors, it was concluded that higher levels of education promote higher recycling rates of EEE. Also, in the environmental factors, it was concluded that environmental tax revenues are an effective measure to promote the CE, since they cause an increase in the recycling rate.

The main limitation of this study was the short period studied. This topic is relevant and urgent, and the only way to study it was to approach this short time frame with adequate data available. Nevertheless, several tests were made to ensure the robustness of the findings guaranteeing that the main outcomes are trustworthy. Another possible limitation is that this subject is fairly recent, and the results can change briefly if these countries adopt different policies and priorities soon. Future research could analyze if the recycling rate increases while the population receives incentives to make their behavior more compatible with the sustainable principles of the CE. Moreover, further studies could apply this approach to different groups of countries and add new factors to study recycling.

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Appendices

Table A.1: Correlation Matrix Values

MODEL I (A)

	LRR	*LWCOL*	*LGERD*	*LGDPPC*	*LEMPS*	*LEMPA*	*LETR*	*LCO2PC*	*LEDU*
LRR	1.000								
LWCOL	0.5489	1.000							
LGERD	0.0971	0.7144	1.000						
LGDPPC	0.0151	0.7243	0.6410	1.000					
LEMPS	-0.0571	-0.0341	0.0000	0.0437	1.000				
LEMPA	0.0639	0.0699	0.0720	-0.0403	-0.4981	1.000			
LETR	0.0024	-0.4281	-0.4517	-0.4619	-0.0758	0.0245	1.000		
LCO2PC	-0.0369	0.2731	0.2595	0.4599	0.0740	-0.0932	-0.0660	1.000	
LEDU	0.1384	0.4248	0.2475	0.5461	-0.0251	0.0427	-0.1379	0.1317	1.000

Model I (B)

	LRR	*LPOP15*	*LPOP65*	*LGERD*	*LGDPPC*	*LEDU*	*LWCOL*	*LCO2PC*	*LETR*
LRR	1.000								
LPOP15	0.0617	1.000							
LPOP65	0.1027	-0.5115	1.000						
LGERD	0.0971	0.2277	0.2032	1.000					
LGDPPC	0.0151	0.5703	-0.2342	0.6410	1.000				
LEDU	0.1384	0.5806	0.0258	0.2475	0.5461	1.000			
LWCOL	0.5489	0.4781	0.0290	0.7144	0.7243	0.4248	1.000		
LCO2PC	-0.0369	0.1468	-0.2938	0.2595	0.4599	0.1317	0.2731	1.000	
LETR	0.0024	-0.0777	-0.0299	-0.4517	-0.4619	-0.1379	-0.4281	-0.0660	1.000