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Performance of EU Countries in Managing Electrical and Electronic Equipment Waste in the Context of the Circular Economy

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PERFORMANCE OF EU COUNTRIES IN MANAGING ELECTRICAL AND ELECTRONIC EQUIPMENT WASTE IN THE CONTEXT OF THE CIRCULAR ECONOMY

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Abstract

In today's context, the circular economy is a model of sustainable economic development that is becoming particularly important for the electrical and electronic waste (e-waste) industry. From this perspective, the research in the article will be carried out for the 27 European Union Member States regarding the performance in managing electrical and electronic waste, also highlighting the changes that have occurred within the analyzed countries in the years 2015 and 2020. The empirical study will adopt a complex econometric tool, represented by hierarchical cluster analysis, with countries grouped into four clusters over two distinct periods (2015 and 2020) where the variables included will be the following: the amount of e-waste generated per capita, the amount of electrical and electronic equipment sold on the market per capita, electrical and electronic waste recycled and prepared for reuse, and the circularity rate. Based on these variables, the article will analyze the performance in e-waste management (gain or loss of performance) in the analyzed years, underlying also the capacity of analyzed countries to adapt to the new demands imposed by the circular economy on the coordinates of sustainable development. In addition, theoretical, methodological, and empirical implications will be presented, which, through their implementation, can influence the managerial and environmental policy decisions.

Keywords: circular economy, e-waste, sustainable development, hierarchical clusters, European Union

JEL Classification: E61, E70, F64, Q43, G53

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Introduction

The problem of a more environmentally friendly economy and sustainable development based on the notion of a circular economy has returned in light of the growing scarcity of natural resources and the difficulties caused by global climate change and the pandemic epidemic. The idea of a circular economy arose in reaction to the need for sustainable development in the context of over-production and over-consumption of natural resources. By progressively uncoupling economic activity from use of scarce resources and reducing waste from the system, the circular economy helps everyone in society (Ellen Macarthur Foundation, 2022). This is why the term circular economy is increasingly being used to describe the way businesses of the future will operate (Burnar, 2022).

The circular economy is particularly important for the e-waste industry, as electric and electronic waste contains toxic substances and precious metals (Pan, Wong and Li, 2022). E-waste has a special place because of its characteristics and the special type of treatment they require (due to the highly polluting materials), otherwise it can be harmful to the human health and environment. Given the importance of ensuring a circular economy and reducing waste, numerous initiatives and action plans have been adopted at European level aiming at a more sustainable design of products, reducing waste (especially electronic and electrical waste) in order to achieve a fully circular, sustainable, carbon-neutral, and toxics-free economy by 2050 (European Parliament, 2022a).

The approach in the article highlights the novelty of linking the concepts of circular economy – sustainable development – e-waste, which is increasingly necessary in the actual international economic and social circumstances, characterized by the pandemic crisis, the energy crisis and the armed conflict in Ukraine. Moreover, from the perspective of the elements that make up this correlation, the e-waste factor proves to be relevant for the current research path and the new approach in the article. Thus, the analysis will be carried out for the 27 Member States of the European Union, in terms of the management of electrical and electronic waste, highlighting the changes that have occurred in the countries analyzed in 2015 and 2020 (preceding and foreshadowing the current energy crisis). The empirical study will adopt a complex econometric tool, represented by the hierarchical cluster analysis, with countries grouped into four clusters over two distinct periods, mentioned above, where the determinant variables will be represented by: amount of e-waste generated per capita, amount of electrical and electronic equipment sold on the market per capita, electrical and electronic waste recycled and prepared for reuse, and circularity rate.

Based on the correlations of these variables, the article will analyze the e-waste management performance (gain or loss of performance) in the two timeframes (2015 and 2020), highlighting the dynamics of the 27 European Union member states' capacity to adapt to the new demands imposed by the circular economy. In this context, the study aims to highlight the innovation aspects and the significance of the performance for e-waste management on both the theoretical and practical level. Paying specific attention to the e-waste in the context of circular economy and sustainable development, the study contributes to nurture the empirical works and to fill in the lack of an integrated correlation able to provide some valid solutions with broad adaptability for EU countries in the current circumstances.

The article is organized into a logical flow of sections to articulate the answers to the research questions. In Section 2, the subjects that constitute the basis of the study are examined and a comprehensive evaluation of the mainstream literature on the performance of e-waste management is given: e-waste, circular economy, sustainable development. In the third section, the study's data, variables, research hypothesis, and the methodology determined to be appropriate were described. Using a hierarchical cluster analysis, the results of the study are presented and discussed in Section 4. All of these analyses and tests are used for the elaboration of the study hypotheses, leading to the formation of meaningful clusters for analysis of results and conclusions. In the final section, the theoretical and practical consequences of the study, as well as the limits and suggestions for further research are presented. From the point of view of conceptualizing the research, the article focused on highlighting the innovativeness and importance of performance for e-waste management, both theoretically and practically.

1. Literature review

The concept of the circular economy is based on transition from a traditional, linear system to a circular system, the waste resulting from consumption becoming a resource. The circular economy is therefore a model of production and consumption that involves reusing, repairing, and recycling existing materials and products for as long as possible. As a result, the life cycle of products will be extended (European Parliament, 2022a). The objective of a circular economy is to close the loop between the industrial process and the cycles of natural ecosystems. It is not just about minimizing damage; it is about designing a system where economic growth and environmental protection flourish hand in hand. Using the products, tools, and equipment as long as feasible, the demand for resources will be drastically reduced, which will form the basis of a sustainable society.

The notion of the circular economy is built on three pillars (DS Smith, 2022) that have arisen in response to the need for sustainable development:

- pollution prevention and waste management. Electronic waste plays a unique role in the waste stream. A circular economy eliminates the negative impacts of economic activity that harm human health and natural systems;
- a circular economy prioritizes the reuse and recycling of components and materials within the economy;
- regeneration and rejuvenation of natural systems. In a circular economy, non-renewable resources are not used while renewable ones are preserved or improved.

As defined by Baldé et al. (2017), e-waste includes any and all electrical and electronic equipment that has been dumped without the aim of being reused.

Electrical and electronic equipment brings great benefits to humanity, but on the other hand, it involves large amounts of resources wasted along their entire value chain, from the extraction of valuable ones, included in the composition of electronic products, to production, transport, retail, and consumption. All of these generate multiple negative impacts, cause a strong environmental footprint, but also highlight the importance of developing effective e-waste management strategies (Lazar, 2021).

According to recent studies, in order to effectively harness the benefits of e-waste recycling without endangering public health, a holistic approach that includes improved product design, recycling rates and minimal release of hazardous e-waste pollutants into the environment is necessary (Ahirwar and Tripathi, 2021). It should be taken into consideration that, for the most part, challenges in e-waste management arise from lack of technical skills, poor infrastructure, inadequate financial support, and inactive community involvement (Rautela et al., 2021). On the other hand, e-waste can also be seen as an opportunity. Collecting resources from electronic equipment can be less polluting than mining, and the electronic equipment in use is worth more than the materials they contain. Therefore, extending the life of products and reusing components would therefore bring even greater economic benefits. Recycling technologies also need to ensure that e-waste is processed in an environmentally friendly way, with high efficiency and a low carbon footprint, at a fraction of the costs involved in setting up expensive melting plants. Considering depleted natural resources, this urban mining approach could generate increased energy efficiency and a decreased demand for new raw materials (Kaya, 2016).

There is also an opportunity to build a more circular system, where resources are not extracted, used, and wasted, but instead valorised and reused in order to create sustainable jobs (Lazar, 2021). But for this to happen, a common legal framework, transformation of the informal sector, enabling technologies, and ownership of various stakeholders and entrepreneurial opportunities are needed (Murthy and Ramakrishna, 2022).

On a global scale, measures to improve e-waste management are recommended that aim to incorporate circular economy principles into the design and production of e-equipment and e-waste management, including urban mining; harmonize key terms and definitions to enable consistency in e-waste management; and improve regulation and recognition of the informal e-waste management sector (Shittu, Williams and Shawb, 2021). Given the importance and the need to implement the circular economy model, plans and action programs on circular economy and waste reduction have been adopted at the European level. These measures are in line with the measures adopted by the United Nations Agenda in September 2015, which identified the 17 goals (SDGs) with the aim of ending poverty, protecting the planet, and ensuring prosperity by 2030. In this context, increasing levels of e-waste, its improper treatment and disposal pose significant environmental and human health challenges (Baldé et al., 2017).

In March 2020, the European Commission presented its Action Plan for the Circular Economy, which includes among its goals a more sustainable design of products, reducing waste (reducing electronic and electrical waste being among its main priorities). The plan sets out specific immediate targets, such as the 'right to repair' and improving reuse capacity, the introduction of a common charger, and a reward system to encourage recycling of electronic products (European Parliament, 2022b).

In February 2021 the European Parliament adopted a resolution on this plan calling for further action to achieve a fully circular, carbon-neutral, sustainable, and toxics-free economy by 2050. Therefore, stricter recycling rules and binding targets for raw material consumption by 2030 are also called for and in the area of e-waste it is encouraged a longer life through reuse and repair. So, from 1 March 2021, the new EU energy label came into force with the aim of extending the life of electronic products and their repair. Given that discarded electronic and electrical equipment contains potentially harmful materials that pollute the environment and increase the risks for those working to recycle this type of waste, the EU has adopted legislation to prevent the use of certain chemicals (European Parliament, 2011).

In March 2022, the European Commission elaborated a first package of measures in order to accelerate the transition to a circular economy as part of the Circular Economy Action Plan.

Proposals include promoting sustainable products, encouraging consumers to go green, reviewing building materials regulations, and a strategy for sustainable textiles (European Parliament, 2022a).

Potential solutions to reduce e-waste problems should be addressed comprehensively, focusing on two fronts: upstream and downstream. Potential upstream solutions should focus on more rational and environmentally friendly consumption habits to reduce quantities of e-waste and increase its recyclability. The downstream solutions should include appropriate actions to reduce the illegal trade in e-waste, through international cooperation and coordination, better enforcement of legislation, along with improved, more affordable and environmentally friendly e-waste recycling technologies (Bakhiyi et al., 2018). Economic, environmental, and social gains from adopting a circular economy are included in the execution of these policies: the use of less natural resources; making businesses more competitive; increasing raw material supply security, fostering innovation, generating new employment opportunities, and fostering economic expansion (European Parliament, 2022b).

E-waste management in the European Union has to be evaluated in the new framework of the circular economy. There is a Europe with two-speed, according to studies on the circular economy, with some countries far ahead of the pack in pursuing circular economy principles (such as Germany, Belgium, Spain, France, Italy, the Netherlands, and the United Kingdom), and another group of EU countries where the transformation to the circular economy is taking place at a slow pace (Central and Eastern European and Southern European countries). These two groupings of nations are at various stages because of the approaches they have taken to the transition to a circular economy and because of other factors related to their social and economic growth (Mazur-Wierzbicka, 2021). To this end, key areas of concern for e-waste management are identified: the partial provision of formal systems for the collection and treatment of e-waste on a global scale; the further escalation of global e-waste generation; and the absence of regulation and implementation (Shittu, Williams and Shawb, 2021).

Recycling and composting, incineration, and landfills are the three types of treatment that determine how well municipal waste management functions. Some authors have explored three types of visualization of municipal waste management performance using the Ternary Diagram Method, and one consistency that has emerged from their work is the correlation between the growth of recycling and composting and the growth of incineration performance over the past 20 years in the EU28 (Pomberger, Sar and Lorber, 2017). Other authors recommend that a five-step performance of waste management systems should be used by decision makers to assess the level of performance at the municipal level and, based on this, identify possible implementation measures, check the level of implementation, monitor progress and compare performance levels in different cities (Campitelli, Kannengießer and Schebek, 2022).

As an effective and prevalent environmental management tool, life cycle analysis can contribute to assessing the environmental performance of e-waste management activities (Xue and Xu, 2017) and the process of preparing for reuse can lead to a more durable electronic device than a new one depending on the set of replaced components (Pini et al., 2019). Also, analyzing consumer behavior towards the end-of-life of electronic equipment is an important aspect in analyzing how to manage e-waste in the circular economy (Islam et al., 2021). To make e-waste management more efficient and effective, the circular economy package should stimulate Europe's transition toward more sustainable resources and energy-oriented waste management. In order to achieve these important goals, addressing e-waste will require international collaboration, economic incentives that protect the workforce, and management approaches that minimize negative environmental and human health impacts (Awasthi et al., 2019).

Paying specific attention to the e-waste in the context of circular economy and sustainable development, the study contributes to complete the existent studies and to fill in the lack of correlations able to provide some valid solutions with broad adaptability for EU countries in the current circumstances.

In this context, the article's research provides structure and draws clear and logical lines with respect to the issues that form the basis of the study's analytic framework. As a result, we came up with the following study inquiries:

- The first research question (RQ1) addresses the following: how can the effectiveness of e-waste management be evaluated in the context of the circular economy?

- The second research question (RQ2) envisions a focus on concerning the management of electronic waste, what are the current and projected trends at the state level?

- The last research question, the third (RQ3), addresses the issue of what are the prospects for the examined nations in accommodating the e-waste management needs of the transition to the circular economy?

2. Research methodology

2.1. The Research objective

The objective of the research is to identify the performance of the EU 27 countries in terms of e-waste management and trends over two years (2015 and 2020), analyzing the evolutions in 2020 compared to 2015. For this approach, hierarchical cluster analysis will be used, as well as techniques and methods to help validate the data, the hypotheses, and finally the cluster structure. Three approaches will be outlined to achieve the research objective: technical (identification of data and variables to be analyzed, establishment of clusters, validation or invalidation of hypotheses), economic (analysis of the performance of the EU 27 countries in e-waste management) and social (implications of good e-waste management in a circular economy).

2.2. Data and variables

In the context of the growing importance of the circular economy, both at the European and global level, the research aims to highlight the performance of the 27 Member States of the European Union in terms of management of electrical and electronic waste, as well as the changes that have occurred between the countries analyzed in 2015 and 2020.

The research was based on data provided publicly by the European Union's statistical service, Eurostat (Eurostat, 2022), as well as by including in the analysis data aggregated by the Global E-waste Statistics Partnership (GESP, 2022), a consortium formed in 2017 by the International Telecommunication Union (ITU), the United Nations University - Sustainable Cycles (UNU-SCYCLE) and the International Solid Waste Association (ISWA). In order to obtain relevant results for both practitioners and the scientific community, the following variables were considered for the research (Table no. 1):

Table no. 1. Descriptive statistics of estimated variables for the year 2025

Variable	Type	U.M.	Data source
EWGen	Amount of e-waste generated per capita	Kg/capita	Global E-waste Statistics Partnership
EEE	Quantity of electrical and electronic equipment sold on the market per capita	Kg/capita	Global E-waste Statistics Partnership
EWRec	Electrical and electronic waste recycled and prepared for reuse	Percent	Eurostat
CIRC	Circularity rate	Percent	Eurostat

Given the difficulty in collecting specific data on e-waste management and the delay in collecting and publishing the relevant information, we found it useful to use multiple data sources, both to correlate common reporting and to have access to the latest available data.

The baseline period for the research conducted was considered to be 2015, a landmark year for the European Union's firm commitment to sustainable development through the adoption of the Paris Agreement on climate change (European Commission, 2015). Given that our research is limited to the most recent published data, i.e. those published for the year 2020, the timeframe available is relatively short (two years, 2015 and 2020), but the results obtained are relevant and provide valuable insights into the performance of EU countries on e-waste management.

Given that the latest data published by the Global E-waste Statistics Partnership was for 2019 and the data provided by Eurostat for the rate of electrical and electronic waste recycled and ready for reuse was limited to 2018, we extrapolated the trend over the period 2015-2019 to obtain relevant data for 2020. For the extrapolation, we used the FORECAST.ETS function available in Excel. According to accepted methodology in the literature, with this function, one can predict a future value based on existing data series using the AAA (Holt-Winters) version of the exponential smoothing algorithm (ETS) (Kays et al., 2018; Hyndman and Athanasopoulos, 2019).

The weights were assigned to the time series data variations directly proportional to the terms of their geometric progression, based on the following exponential scale: {1, (1 - α), (1 - α)2, (1 - α)3, ..., ∞} (Held, Moriarty and Richardson, 2018). The descriptive statistics of the variables used in this research for the 27 EU Member States are presented in Table no. 2.

Table no. 2. Descriptive statistics of the variables analyzed for the years 2015 and 2020

Variable	Year 2015				Year 2020			
	Min.	Max.	Mean	Standard deviation	Min.	Max	Mean	Standard deviation
EWGen	9.8	22.8	15.7	4.0836	10.6	22.4	16.4	3.6030
EEE	10.3	25.4	17.9	4.1461	12.3	25.7	19.2	3.7001
EWRec	65.1	92.5	82.2	6.9643	71.4	93.1	83.9	5.4295
CIRC	1.7	25.8	8.2	5.9750	1.3	30.9	10.2	7.4622

The analysis of e-waste management performance and the performance gain or loss that occurred during the period under review was carried out by a complex econometric tool using hierarchical cluster analysis, thus answering research question IC1 (How can e-waste management performance be analysed in the context of the circular economy?). Cluster analysis aims to group similar variables so that the degree of association between two variables is as high as possible if they belong to the same group, and as low as possible if they belong to different groups.

According to published literature, the use of cluster analysis aims to identify potential hidden structures in the data series under analysis, without providing detailed explanations or causal interpretations, but offering an alternative way of approaching and interpreting selected variables (Jain, Murty and Flynn, 1999). In order to use hierarchical cluster analysis, a series of specific tests and methods were carried out, represented by the Shapiro-Wilk test (for data distribution analysis), the Euclidean squared distance method (to generate the closeness matrix), and the Ward method (for cluster analysis) were all performed in order to implement this technique (to determine the distance between clusters). Welch and Brown-Forsythe tests will be performed to determine whether or not the clusters discovered for the two years under study are statistically significant (2015 and 2020). To ensure that the clusters that have been found and confirmed are indeed representative, an ANOVA test will be performed. Within this broad context, bounded by data, variables, methods, and analysis techniques specific to the study, the hypotheses to be tested identified by the research questions are the following: H1. The variables of the analysis are characterized by a normal distribution; H2. Cluster analysis, including cluster validity, is the main research method; H3. The values obtained from the analysis of the variables show uniform increasing trends for the intervals analyzed; H4. The performance of the EU27 countries in e-waste management helps to identify the performance clusters in the analyzed time intervals.

3. Results and discussions

By applying the specific methodology of cluster analysis in our research, we aimed to identify the performance of the EU countries in managing electrical and electronic waste, based on aggregated data from available sources. This clustering approach offers the possibility to obtain a clear picture of the groups of performing countries alongside the countries with more modest performance.

Also, by analyzing and comparing the composition of the groups identified for the two distinct periods considered, we can highlight the dynamics of each country's adaptation to the demands of the transition to a green economy, particularly in the management of electrical and electronic waste.

In order to test the validity of the assumptions required for the application of the cluster analysis, according to the currently accepted methodology, the selected variables were examined whether they follow a normal distribution by using the Shapiro-Wilk test (Shapiro and Wilk, 1965; Yap and Sim, 2011). The results obtained (Table no. 3 and Table no. 4) confirm the existence of a normal distribution.

Table no. 3. Normality test (Kolmogorov-Smirnov*) for the years 2015 and 2020

Variable	Year 2015			Year 2020		
	Statistic	df	Sig.	Statistic	df	Sig.
EWGen	0.146	27	0.148	0.147	27	0.137
EEE	0.107	27	0.200*	0.137	27	0.200*
EWRec	0.155	27	0.193	0.116	27	0.200*
CIRC	0.142	27	0.170	0.139	27	0.193

*Note: * the lower limit of true significance, a correction of Lilliefors significance*

Table no. 4. Normality test (Shapiro-Wilk) for the years 2015 and 2020

Variable	Year 2015			Year 2020		
	Statistic	df	Sig.	Statistic	df	Sig.
EWGen	0.920	27	0.139	0.938	27	0.111
EEE	0.966	27	0.502	0.945	27	0.161
EWRec	0.916	27	0.131	0.953	27	0.247
CIRC	0.879	27	0.105	0.900	27	0.014

Analyzing the results obtained, and taking into account the existing literature (Shapiro and Wilk, 1965; Weber, Leemis and Kincaid, 2006) the results provided by normality show that the available data follow a normal distribution; there is, however, a reasonable suspicion that the variables might show some deviations from the normal distribution. Nevertheless, in line with the literature and taking into account the sample size and the low impact of the distribution type on the variables (Psaradakis and Vávra, 2020; Yap and Sim, 2011), we consider it justified to use the whole dataset for the hierarchical cluster analysis. Thus, hypothesis 1 was validated, allowing for further analysis.

In order to construct the proximity matrix, the squared Euclidean distance method (1) (Punj and Stewart, 1983) was chosen, and the Ward method (2) was used to determine the distance between clusters. According to the literature, the Ward Method has been shown to be more performant than other methods specific to clustering classification in producing homogeneous and interpretable clusters, bringing added robustness to the results (Punj and Stewart, 1983; Harrigan, 1985; Everitt, Landau, and Leese, 2011):

$$W = \left\| w_{ij} \right\|_{i=\overline{1,n}, j=\overline{1,n}}, \quad w_{ij} = \sqrt{\sum_{i=1}^{n} \left(z_{ik} - z_{ij} \right)^2}, \; j = \overline{1,m}, \; k = \overline{1,m} \; j \neq i, \; k \neq i, \; w_{ii} = 0 \tag{1}$$

$$\Delta(A,B) = \sum_{i \in A \cup B} \left\| x_i - m_{A \cup B} \right\|^2 - \sum_{i \in A} \left\| x_i - m_A \right\|^2 - \sum_{i \in B} \left\| x_i - m_{\mathbf{B}} \right\|^2 - \frac{n_{A \cap B}}{n_{A \cup B}} \left\| m_A - m_B \right\|^2 \tag{2}$$

The next step of the analysis involved determining the optimal number of clusters for each period analyzed, taking into account the clustering patterns and cluster dendrogram of the three periods analyzed (Salvador and Chan, 2004; Everitt, Landau and Leese, 2011). The Euclidean squared distance method (Everitt, Landau and Leese, 2011) was used to construct the proximity matrix in the cluster identification algorithm, then the Ward method (Ward, 1963) was used to determine the distance between clusters. The solution that best corresponded to the cluster analysis for the years 2015 and 2020 was a four-cluster solution, giving the most relevant results, thus minimizing the differences existing within clusters while maximizing the differences existing between clusters. The adopted solution is based on existing literature (Jain, Murty and Flynn, 1999; Jung et al., 2003) on optimal cluster segmentation (Figure no. 1 and Figure no. 2).

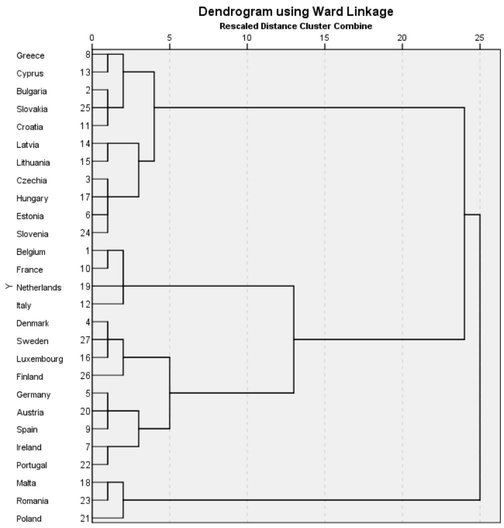

Figure no. 1. Dendrogram for 2015

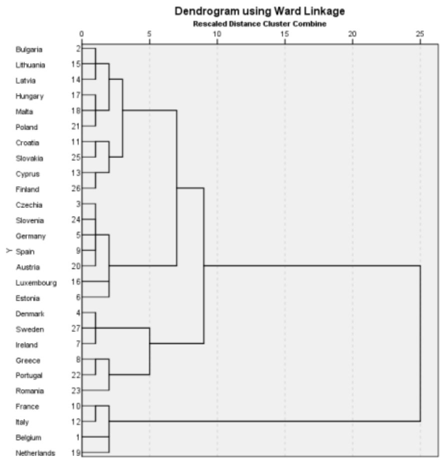

Figure no. 2. Dendrogram for 2020

Since clusters of unequal size were identified, in order to test the validity of the clusters we decided to use the Welch test and the Brown-Forsythe test (with null hypothesis H1, respectively, H2 - the means of the variables do not differ significantly). The results of the tests (significance threshold $\alpha = 0.05$) for the clusters identified in 2015 and 2020 are shown in Table no. 5 and Table no. 6.

Table no. 5. Welch and Brown-Forsythe test results for 2015

		Statistic[a]	df1	df2	Sig.
EWGen	Welch	22.713	3	7.021	0.001
	Brown–Forsythe	26.407	3	9.030	0.000
EEE	Welch	11.161	3	6.913	0.005
	Brown–Forsythe	13.560	3	13.212	0.000
EWRec	Welch	33.805	3	7.999	0.000
	Brown–Forsythe	21.469	3	18.412	0.000
CIRC	Welch	12.235	3	6.183	0.005
	Brown–Forsythe	13.225	3	7.225	0.003

Note: [a] *Asymptotic distribution F*

Table no. 6. Welch and Brown-Forsythe test results for 2020

		Statistic[a]	df1	df2	Sig.
EWGen	Welch	8.006	3	10.822	0.004
	Brown–Forsythe	6.412	3	16.524	0.004
EEE	Welch	2.492	3	9.779	0.021
	Brown–Forsythe	2.856	3	16.382	0.049
EWRec	Welch	5.255	3	9.400	0.021
	Brown–Forsythe	6.389	3	13.339	0.006
CIRC	Welch	34.037	3	9.190	0.000
	Brown–Forsythe	44.233	3	8.530	0.000

Note: [a] *Asymptotic distribution F*

Given the positive results provided by the Welch and Brown-Forsythe robust tests confirming the validity of the identified clusters for the two analyzed periods, according to the literature (Shapiro and Wilk, 1965; Yap and Sim, 2011; Kays et al., 2018; Firoiu et al., 2021), it follows that we can apply the ANOVA methodology in order to confirm the representativeness of the identified clusters. The results obtained are presented in Table no. 7 and Table no. 8. As a result, hypothesis 2 was validated.

Table no. 7. ANOVA results for the year 2015

		Sum of squares	df	Mean squares	F	Sig.
EWGen	Between groups	333.436	3	111.145	25.532	0.000
	Within groups	100.125	23	4.353		
	Total	433.561	26			
EEE	Between groups	284.301	3	94.767	13.401	0.000
	Within groups	162.646	23	7.072		
	Total	446.947	26			
EWRec	Between groups	868.921	3	289.640	16.989	0.000
	Within groups	392.119	23	17.049		
	Total	1261.040	26			
CIRC	Between groups	653.806	3	217.935	18.267	0.000
	Within groups	274.401	23	11.930		
	Total	928.207	26			

Table no. 8. ANOVA results for the year 2020

		Sum of squares	df	Mean squares	F	Sig.
EWGen	Between groups	149.327	3	49.776	6.083	0.003
	Within groups	188.194	23	8.182		
	Total	337.521	26			
EEE	Between groups	99.781	3	33.260	2.986	0.042
	Within groups	256.178	23	11.138		
	Total	355.959	26			
EWRec	Between groups	372.274	3	124.091	7.240	0.001
	Within groups	394.200	23	17.139		
	Total	766.474	26			
CIRC	Between groups	1276.331	3	425.444	57.074	0.000
	Within groups	171.447	23	7.454		
	Total	1447.779	26			

Based on the analysis carried out, for 2015 we can identify four relevant clusters. Cluster A-2015 includes 4 countries, namely Belgium, France, Italy,, and the Netherlands. Cluster B-2015 groups 11 Member States, namely Bulgaria, Czech Republic, Estonia, Greece, Croatia, Cyprus, Latvia, Lithuania, Hungary, Slovenia and Slovakia. The third cluster, C-2015, groups 9 European countries, namely Denmark, Germany, Ireland, Spain, Luxembourg, Austria, Portugal, Finland, and Sweden. The last cluster, D-2015, brings together the last three Member States, namely Malta, Poland, and Romania. For 2020, the same grouping was maintained into four clusters, but their composition differs slightly, depending on the evolution of the variables analyzed. Thus, the A-2020 cluster groups 4 European countries: Belgium, France, Italy and the Netherlands. Cluster B-2020 brings together 10 EU countries, namely Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Slovakia, and Finland. Cluster C-2020 groups 7 European countries, namely the Czech Republic, Germany, Estonia, Spain, Luxembourg, Austria, and Slovenia. The fourth cluster, D-2020, brings together six EU countries: Denmark, Ireland, Greece, Portugal, Romania, and Sweden. The characteristics of the clusters identified in 2015 and 2020 are presented in table no. 9.

Table no. 9. Values of variables for clusters in 2015 and 2020

Cluster	EW Gen	EE E	EWRe c	CIR C	Cluster	EW Gen	EE E	EWRe c	CIR C
A-2015*	**19.8**	**21.2**	**81.8**	**19.9**	**A-2020***	**20.1**	**22.0**	**78.5**	**24.4**
Belgium	20.3	21.7	77.4	17.7	Belgium	20.4	22.9	71.4	23.0
France	20.1	23.1	81.9	18.7	France	21.0	23.5	80.3	22.2
Italy	17.8	17.1	85.7	17.2	Italy	17.5	16.9	83.2	21.6
Holland	21.1	22.7	82.1	25.8	Holland	21.6	24.7	78.9	30.9
B-2015*	**12.7**	**14.4**	**86.1**	**5.4**	**B-2020***	**13.6**	**17.0**	**86.7**	**5.9**
Bulgaria	10.3	12.0	85.6	3.1	Bulgaria	11.7	13.7	83.9	2.6
Czech Rep.	14.5	18.4	82.5	6.9	Croatia	11.9	16.1	93.1	5.1
Estonia	12.1	14.7	86.7	11.3	Cyprus	16.8	18.5	89.1	3.4
Greece	16.6	14.0	89.6	1.9	Latvia	10.6	12.3	83.5	4.2
Croatia	10.6	12.5	92.5	4.6	Lithuania	12.3	14.8	84.4	4.4
Cyprus	16.5	15.9	91.0	2.4	Hungary	13.6	19.7	84.1	8.7
Latvia	10.0	10.3	82.2	5.3	Malta	14.5	18.3	87.2	7.9
Lithuania	11.2	12.1	80.7	4.1	Poland	11.7	16.7	81.6	9.9
Hungary	11.8	16.6	83.3	5.8	Slovakia	12.8	16.7	89.7	6.4
Slovenia	14.2	17.0	86.2	8.6	Finland	19.8	23.5	90.4	6.2
Slovakia	11.6	15.0	86.7	5.1	**C-2020***	**17.1**	**19.1**	**86.8**	**13.3**
C-2015*	**19.1**	**21.2**	**82.7**	**7.3**	Czech Rep.	15.7	16.4	86.3	13.4
Denmark	22.8	22.6	84.2	8.3	Germany	19.4	18.2	85.8	13.4
Germany	19.7	21.0	79.3	12.0	Estonia	13.1	17.0	90.3	17.3
Irland	18.1	21.4	83.2	1.9	Spain	19.0	20.5	88.8	11.2
Spain	18.5	19.6	75.7	7.5	Luxem.	18.9	25.1	89.2	13.6
Luxem.	18.7	23.8	86.9	9.7	Austria	18.8	17.8	80.5	12.0
Austria	19.3	19.7	81.1	10.7	Slovenia	15.1	18.8	86.4	12.3
Portugal	16.2	15.4	78.0	2.1	**D-2020***	**17.7**	**21.1**	**79.5**	**4.3**
Finland	18.9	22.2	92.5	6.4	Denmark	22.4	23.9	82.3	7.7
Sweden	19.8	25.4	83.6	6.7	Irland	18.7	25.7	85.0	1.8
D-2015*	**11.2**	**16.3**	**66.9**	**6.0**	Greece	16.9	17.5	76.0	5.4
Malta	14.1	19.0	65.1	4.6	Portugal	16.6	20.1	78.7	2.2
Poland	9.8	15.5	69.7	11.6	Romania	11.4	15.9	71.5	1.3
Romania	9.8	14.3	66.0	1.7	Sweden	20.1	23.4	83.3	7.1

*Note: * average value at cluster level*

A main conclusion of the research carried out indicates that in the periods analyzed, 2015 and 2020, the average values of the variables analyzed were on an upward trend, which shows a constant concern at the EU Member State level to improve performance in terms of electrical and electronic waste management. Thus, the hypothesis 3 was validated.

During the period selected for analysis, on average, the amount of e-waste generated per capita (EWGen) increased by 4.46%, while the amount of electrical and electronic equipment sold on the market per capita (EEE) increased by 7.26%. This outlook is not necessarily positive, if we consider the production and consumption of electrical and electronic equipment, but if we look at the rate of electrical and electronic waste recycled and prepared for reuse (EWRec), we notice that this also increased by 2.07%, and the circularity rate (CIRC) increased considerably, by 24.39% in 2020 compared to 2015. In other words, in the years 2015 and 2020, EU countries are registering an increase in the production and sale of electrical and electronic equipment, which generates an increased amount of specific waste, but concerns about the management of this waste are growing, with the circularity rate increasing by almost 25%.

In order to better observe the clusters of countries at the level of each year analyzed, as well as to more easily follow the evolution of the values of the variables characterizing the identified clusters, we have centralized this information in Table no. 10.

Table no. 10. Cluster characteristic values for 2015 and 2020

Cluster	EWGen	EEE	EWRec	CIRC
A-2015*	19.8	21.2	81.8	19.9
B-2015*	12.7	14.4	86.1	5.4
C-2015*	19.1	21.2	82.7	7.3
D-2015*	11.2	16.3	66.9	6.0
Mean UE 2015	**15.7**	**17.9**	**82.2**	**8.2**
A-2020*	20.1	22.0	78.5	24.4
B-2020*	13.6	17.0	86.7	5.9
C-2020*	17.1	19.1	86.8	13.3
D-2020*	17.7	21.1	79.5	4.3
Mean UE 2020	**16.4**	**19.2**	**83.9**	**10.2**

*Note: * average value at cluster level*

Regarding the performance of EU countries in managing electrical and electronic waste, the analysis revealed that four performance groups can be identified in 2015. Cluster A-2015 brings together the 4 best performing countries at European level (Belgium, France, Italy, and the Netherlands). About these four countries, the research highlights the extremely high circularity rate compared to the rest of the Member States, almost three times higher than the rest of the countries included in the analysis.

The next group of EU countries in terms of their performance in managing electrical and electronic waste in 2015 was isolated by cluster C-2015. The nine countries in this cluster show a relatively similar performance to the specific performance of cluster A-2015, the main difference being the average circularity rate, which is less than half (41.2%).

The next two clusters of EU countries in 2015, in terms of the objectives of the research carried out, were grouped in clusters B-2015 and D-2015. It is relatively difficult to determine which one of the two clusters is the worst in performance, considering the management of electrical and electronic waste in 2015. By comparing the performance in terms of the rate of electrical and electronic waste recycled and prepared for reuse and the rate of circularity as a good predictor of performance, we can say that the three European countries (Malta, Poland and Romania) that made up cluster D-2015 showed the worst performance. Thus, the rate of electrical and electronic waste recycled and prepared for reuse (EWRec) had an average value of 66.9% (18.61% lower than the EU average) and the circularity rate values were at an average of 6.0% (26.83% lower than the EU average). It should be noted that within this group of countries, Romania has the lowest absolute values of the circularity rate (1.7%) and Malta shows the worst absolute performance in terms of the rate of electrical and electronic waste recycled and prepared for reuse (65.1%).

Following the above-mentioned methodology, we have resumed the analysis for the values of the variables recorded in 2020, in order to be able to highlight the evolution compared to 2015, but also to observe if there are changes between the performance groups, i.e., if there were differences in performance between the different countries considered in the analysis.

The research showed that the same group of four countries (Belgium, France, Italy and the Netherlands) outperformed the other European countries in 2020 and were grouped in the A-2020 cluster. On average, the differences in performance between this group of countries and 2015 were +1.52% for the EWGen variable, +3.77% for the EEE variable, -4.04% for the EWRec variable and +22.61% for the CIRC variable. Thus, hypothesis 4 has been validated for 2015 and 2020.

Analysis of the results shows a slight decrease in performance in terms of the rate of electrical and electronic waste recycled and prepared for reuse, possibly due to the increase in the amount of waste generated per capita and the amount of electrical and electronic equipment sold on the market per capita. However, most relevant in the context of the current research is the significant increase in the average circularity rate for this group of countries, from 19.9% in 2015 to 24.4% in 2020, with the Netherlands having the highest absolute value among the EU countries in 2020 (30.9%).

Following the four best performing countries at EU level, seven countries were grouped in the C-2020 cluster, namely the Czech Republic, Germany, Estonia, Spain, Luxembourg, Austria, and Slovenia. It should be noted that compared to the cluster corresponding to 2015 (cluster C-2015), a number of changes occurred in 2020, which indicates that differences in performance between the EU Member States emerged during the period analyzed. Thus, in 2020, the Czech Republic, Estonia, and Slovenia increased their relative performance, while Denmark, Ireland, Portugal, and Finland were placed in other, lower-performing clusters.

The third group of countries in terms of proven performance in the management of electrical and electronic waste is the B-2020 cluster of 10 EU Member States. Also, for this cluster, we can note that the research carried out highlights the changes that have occurred during the period under review, including Malta and Poland, which have shown a higher commitment and significantly improved their values for the variables analyzed, especially in terms of the rate of electrical and electronic waste recycled and prepared for reuse.

In 2020, the D-2020 cluster brought together six European countries (Denmark, Ireland, Greece, Portugal, Romania, and Sweden), which form the group of EU countries showing some limitation of potential in terms of efficient management of electrical and electronic waste. In this case, the research shows a surprising result, by placing countries with a tradition of promoting a sustainable and green economy (Denmark, Sweden, Ireland) in the group of countries with a more modest performance in terms of e-waste management. The explanation for this grouping is that although in absolute values the rate of electrical and electronic waste recycled and prepared for reuse, as well as the rate of circularity, are higher than the D-2020 group average, the values are still lower than the EU average and, most importantly, there have been reductions in values since 2015, suggesting a decline in performance. Unfortunately, Romania still shows the absolute worst performance at the EU level in terms of circularity rate (1.3%) and the second worst absolute performance in terms of the rate of electrical and electronic waste recycled and prepared for reuse (71.5%).

It is clear that the potential of the countries placed in the D-2020 group is higher than the research results indicate, but it is clear that substantial and sustained efforts are needed to consistently increase the level of performance in the management of electrical and electronic waste in the future.

In summary, based on the detailed analysis presented above, the second research question, IC2 (What are the trends in performance gains or losses in e-waste management at the level of the analysed countries?) was answered.

Conclusions and recommendations

Findings and contributions of the study. Theoretical and methodological implications

The theoretical contribution of the work is substantial, current, and open to future application at scale in the study of literature on e-waste and the circular economy. This study improves our understanding of the theoretical foundations of e-waste management and the e-waste management practices of the EU's member states within the broader frameworks of circular economy and sustainable development.

The study's first step was to try to determine which factors (e-waste generation per capita, electrical and electronic equipment sales on the market per capita, electrical and electronic waste recycled and prepared for reuse, circularity rate) would be most useful in determining EU countries' performance in managing e-waste and the performance gain or loss achieved by these countries. The selection of two study periods (2015 and 2020) has also enabled the structuring of a foundation for measuring the EU 27 nations in the context of their evolving economic, social, and technical situations.

The examination of data from two study periods and from four cluster groups of EU 27 nations revealed significant differences in the management of e-waste. With this clustering method, both the groups of high- and low-performing nations may be easily identified. Thus, in both time periods, the countries in the first cluster (Belgium, France, Italy, and the Netherlands) have recorded superior performance than the other European member states, which indicates the existence of gaps between the categories of states analyzed in terms of electronic waste management. By analyzing and comparing the composition of the groups identified for the two distinct periods, it was possible to highlight the dynamics of each country's adaptation to the demands raised by the transition to a green economy.

Research in the future based on fresh data that still leads to the same cluster structure, particularly the group with the highest performing nations, may help build a standardized approach to e-waste management that can be used throughout Europe.

Findings and contributions of the study. Managerial and policy implications

In light of the fact that electronic waste is one of the fastest growing waste streams, this study aims to present a fresh perspective on the e-waste performance by addressing the lack of legislation, common procedures, or flows of activities that, once implemented, could provide practical frameworks for mitigating the threats to e-waste workers' health and safety on the job, as well as environmental and occupational safety and labor issues.

The average values of the variables studied indicate an increased trend during the examined years (2015 and 2020), suggesting a persistent concern at the level of the EU Member State to enhance performance in the management of electrical and electronic waste. There has been an uptick in the production and sale of electrical and electronic equipment in the analyzed EU countries, leading to a higher volume of specific waste; however, there has also been an uptick in the rate of recycling and preparation of electrical and electronic waste for reuse (2.07%) and a rate of circularity (almost 25%).

Regulations in this area need to be clear and explicit, standards need to be in place, and independently audited activities need to be in place, all while constant monitoring of e-waste management performance is implemented at the EU level to ensure that improvements are made. However, the effectiveness of rules depends on their accurate interpretation by the authorities, who may play an important role in implementing regulations by doing things like ensuring that a sufficient collecting infrastructure is in place and providing assistance for implementation. With the help of other waste streams, governments should establish an e-waste information system (e-waste inventories, producer registration, and fee administration).

Furthermore, all actors in the value chain should be involved in order to ensure the long-term sustainability of the e-waste management system. E-waste management efficiency may also be greatly improved by public education and encouraging more responsible conduct. On the other hand, new technologies are enhancing the efficiency with which electronic waste is repurposed. Policies may be modeled after those of nations with a proven track record of success in the management of e-waste. As a result, the potential for e-waste aggregation, resulting in cost savings and the execution of an integrated plan, may be increased via the harmonization of state management systems. There is potential for European nations to work together on regional initiatives to tackle the many problems associated with e-waste. One possible advantage is that collective action may be taken to better manage electronic waste, which can then be recycled or reused, contributing to sustainable development within the framework of a circular economy. All these conclusions are answers to question IC3: What are the possibilities for the countries analysed to adapt to the requirements of the transition to the circular economy in terms of e-waste management?

Research limitations

Despite the research's shortcomings, we think it may serve as a springboard for other studies that may help expand upon the current body of work in many ways.

First, there is a lack of timely and accurate data on the management of e-waste due to the difficulties of collecting and releasing this information. Thus, in order to connect similar reports and have access to the most current data, the research used a wide variety of data sources. Another restriction is the short time period covered by the study (2015-2020), but we still think the data are useful and may shed light on the progress made by EU nations in e-waste management.

There is also a lack of stability due to the rapid pace of today’s economic, social, and technical changes, making it difficult to create and execute long-term policies at the EU level that would provide a united approach to performance in e-waste management.

Final thought, the answers are not perfect, but they would be much better if the EU and its Member States adopted consistent tactics and actions. The management and policy implications of the study are useful, and might be reinforced by including up-to-date information and data, notwithstanding the limitations noted above, which could be addressed by subsequent research.

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