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Does digitalization foster the path to a circular economy? An exploratory analysis of European Union countries

Mercedes Gil-Lamata | Lucio Fuentelsaz | María Pilar Latorre-Martínez

Department of Business Organisation, University of Zaragoza, Zaragoza, Spain

Correspondence
Mercedes Gil-Lamata, Gran Vía Santiago Ramón y Cajal, 2, 50005 Zaragoza, Spain.
Email: mercedesgil@unizar.es

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Abstract

European Union (EU) governments are placing intensified stress on both the development of the circular economy (CE) and digital performance. In spite of the strategic and economic relevance of these two scientific fields, there is a lack of evidence regarding their mutual effects and implications. We tackle this gap by analysing how digitalization favours the path towards the CE across EU member states. Firstly, a cluster analysis was conducted to identify groups of EU countries depending on circular behaviour, resulting in the Generators, Recyclers, Achievers, Innovators classification. Subsequently, an analysis of variance was performed to examine how the groups were influenced by the different contexts of digitization. This has allowed us to detect that the digitalization variables of human capital, integration of digital technology and digital public services, are key drivers of variability in the CE. Moreover, we have found that countries with similar circular behaviour share similar levels of digitalization variables.

KEYWORDS
circular economy, digitalization, European Union, human capital, sustainable development

1 | INTRODUCTION

The pressure caused by the continuous growth of the world's population and the constant decrease in the amount of non-regenerative resources on a global scale has necessitated a change in the social, environmental and economic production paradigm. The consistent need to seek responsible approaches to production and consumption has been established as a global objective by the United Nations (del Río Castro et al., 2020; Mio et al., 2020). Consequently, for some years now, the focus on a linear economy has transformed into a focus on the circular economy (CE) as an economic model aimed at achieving the challenges of environmental degradation while generating sustainable economic development (Korhonen et al., 2018).

The origins of CE are rooted in the idea of sustainable development (Bruel et al., 2019). That is, the greater the efficient use of resources, the greater the reduction of their negative impact on the environment. All this is under the pursuit of a common goal: sustainable economic growth (Antikainen et al., 2018; Millar et al., 2019). This increasing interest in promoting the diffusion of the CE paradigm as an alternative to the linear model has resulted in a continuous search for alternatives to conduct business more sustainably in the hope of tackling the sustainability crisis (Cezarino et al., 2019). In recent studies, the CE approach has gained momentum as a viable method of simultaneously achieving environmental and economic objectives (Kirchherr et al., 2017). Nevertheless, it requires the involvement of all social actors: the government, businesses and society, as well as their commitment to and participation in the transition process.

For example, the European Union (EU) has launched programmes such as the European Green Deal and the European Circular Economy Action Plan, the main purposes of which are to decouple the use of resources from economic growth in order to generate sustainable consumption and production systems (European Commission, 2018). Interest in CE has thus steadily grown in the EU, with the aim of promoting the responsible and cyclical use of resources with subsequent contributions to sustainable development (Belmonte-Ureña et al., 2021; Puntillo, 2022). Clearly, the CE could bring significant benefits such as creating a net economic benefit of almost two trillion, two million additional jobs by 2030 in the EU, or reducing CO_2 emissions by 48% (EMAF, 2015). Accordingly, the European Commission has established a monitoring framework regarding the CE, which consists of four main areas, further discussed in Section 2.1, composed of different indicators in order to provide access to relevant data for citizens and policymakers with the purpose of supporting progress in tracking the CE (European Commission, 2021). Equally relevant is the Ellen MacArthur Foundation, a pioneering charity that has been fostering CE since 2010, promoting and developing the CE concept, working with businesses, policymakers and academics (EMAF, 2017). Similarly, in 2015, the United Nations established 17 Sustainable Development Goals (SDGs), to be achieved by 2030 (Mio et al., 2020).

From a business perspective, despite its economic impact, information on how CE is reported and conveyed to stakeholders remains scarce (Jabbour et al., 2020; Ki et al., 2020). This lack of clear demarcation can sometimes lead to confusion about what CE entails, meaning that it is necessary for companies to provide more precise information about their CE practices. As a result, most of the studies conclude by alleging that CE demands more empirical content (de Jesus & Mendonça, 2018). Similarly, some researchers have underlined that it is also crucial that society is involved in the transition towards a CE, and have highlighted their role as a key agent in circularity (de Jesus & Mendonça, 2018; Pérez-Cornejo et al., 2020). CE cannot be understood without a circular society, since it requires society's commitment and active participation (Kowalczyk & Kucharska, 2020; Mostaghel & Chirumalla, 2021). In this sense, Centobelli et al. (2020) have established that digital technologies play a key role in the development of a circular society because they facilitate management commitment and support to the implementation of practices to accelerate the circular transformation (Centobelli et al., 2020).

After highlighting the importance of the CE, it is necessary to point out that its implementation would not be free from difficulties. Indeed, CE must overcome financial, institutional and information barriers (Klein et al., 2022). In order to alleviate these difficulties, Antikainen et al. (2018), found that digitization could help the proper implementation of a CE, as digitalization allows companies to develop more efficient processes, thus helping to minimise waste and promoting longer product lifetimes (Antikainen et al., 2018).

The interaction between CE and digitalization is increasingly attracting interest (Brenner & Hartl, 2021) because research has found that digitalization conveys synergies that facilitate the transition from a linear economy to a CE (Grafström & Aasma, 2021). Specifically, a systematic review of the literature has shown that digitization helps the measurement of CE, in addition to tracking the product life cycle (Chauhan et al., 2022). Therefore, digitization, and specifically the use of digital technologies, cannot be overlooked as enablers for promoting CE (Awan et al., 2021). Notwithstanding, their mutual effects, and despite the clear interaction between these two dimensions, the full comprehension of their implications remain under-researched. The few existing studies are qualitative in nature (Ranta et al., 2021), meaning there is a significant need for quantitative research.

To fill this research gap, our objective is to analyse how digitalization influences the CE, in order to see whether technological development favours the implementation thereof. Specifically, we will consider the four main areas of the European Commission framework regarding CE: *production and consumption*, *waste management*, *secondary raw materials* and *competitiveness and innovation*. We also seek to examine which of these digital indicators act as drivers to the CE, and provide implications of adopting digital technologies in the CE transition. In order to achieve this objective, our research question is established as follows: Does digitalization foster the path towards a CE? To this end, this study will conduct a cluster analysis and analysis of variance study covering the period 2014–2021 for a sample of 27 EU countries. In this way, an exploratory analysis will be carried out that allows the study of different strategic groups by country according to the CE. The interaction effect of these groups with digitalization is then analysed. We focus on a country level analysis in the EU on the grounds that the European Commission has significantly increased the number of CE policies to reduce the use of virgin materials while promoting the use of secondary raw materials (European Commission, 2018). Accordingly, our contribution is twofold: on the one hand, we contribute to the limited knowledge of the relationship between CE and digitalization through a preliminary quantitative analysis, with the aim of improving the literature's knowledge regarding the digitalization variables that influence CE. On the other hand, we present a group characterisation of EU countries according to their circular behaviour.

The remainder of the study is organised as follows. Section 2 presents the CE and digitalization background. The sample and variables are set out in Section 3, while the results are discussed in Section 4. Finally, the most relevant findings, as well as their implications, limitations and future research directions are found in Section 5.

2 | BACKGROUND

2.1 | The CE

There is no unified definition of CE (Betancourt Morales & Zartha Sossa, 2020; Kirchherr et al., 2017). Nevertheless, a widely known approach is provided by the Ellen MacArthur Foundation: 'an industrial economy that is restorative or regenerative by intention and design' (EMAF, 2013). The emphasis is on the restoration or regeneration of materials as there is an increasing demand for raw materials due to the high rate of consumerism across the globe.

The importance of CE is demonstrated, on the one hand, by the need for raw materials, and the significant annual growth of consumption on the other hand. In response to the increasing demand for raw materials, measures such as recycling have been introduced (Ranta et al., 2018) with the aim of alleviating the climate emergency. For example, the recycling rate of municipal waste increased in the EU from 27.3% in 2000 to 47.7% in 2019 (European Commission, 2021).

However, this measure does not seem to be sufficient, on the grounds that most waste is not recycled and the process is very slow. In addition, consumption has continued to rise exponentially, increasing the ecological footprint year after year (EMAF, 2015). Therefore, there is a clear need to look for new tools to help the transition from a linear economy to a CE. Accordingly, the European Commission has set up four key areas in order to monitor the CE framework. The first key area is *production and consumption*, critical for progress towards CE, as it is responsible for measuring the waste generated by households, businesses and public institutions that have been both collected and disposed of it. Another key area is *waste management*, understood as the share of waste that is recycled and actually returned into the economic cycle (European Commission, 2021). *Secondary raw materials* are essential on the grounds that recycled materials replace newly extracted natural resources in such a way that the environmental footprint is reduced and, at the same time, leads to an increase in the security of the future supply of raw materials (European Commission, 2021). The final European Commission CE area, *competitiveness and innovation* focuses on investment in the reusing, repairing and recycling sectors. This is because it improves product design for easier re-use and simultaneously, fosters innovative industrial processes. In the long term, this behaviour may contribute to the increasing self-sufficiency of selected raw materials (European Commission, 2021).

2.2 | Digital technologies and the CE

The ongoing digital transformation can serve as an enabler and even a catalyst of CE (Ingemarsdotter et al., 2020). The aim of CE is to optimise resources by increasing their efficiency or by improving product life cycle (Bag et al., 2020). As far as digitalization is concerned, this can give industries a boost as it can close material loops by providing information such as the location, availability or condition of the products (Antikainen et al., 2018). It is for this reason that digital technologies are considered to be part of the fourth industrial revolution, usually known as Industrial Internet or Industry 4.0 (Bag et al., 2020), which enables organisations to better compete in an economic environment that is constantly changing as technology evolves. Therefore, there is a connection between the two concepts, both of which revolve around resource efficiency in which synergies can be created. Digitalization facilitates the improved performance of the CE activities needed in an efficient manner. Accordingly, it could drive the transformation towards a CE, as the introduction of digital technologies has been found to be the greatest ally for conserving resources, reducing asymmetries and facilitating circular systems (Moreno & Charnley, 2016), while also strengthening competitiveness. Moreover, digital technologies can enable CE business models and act as triggers for new CE business models (Marrucci et al., 2022; Ranta et al., 2021). The development of digitalization is thus driving a shift towards new CE practices (Stock et al., 2018).

The extant literature concerning the relationship between digitalization and CE has mostly focused on conceptualising how digital technologies enable the slowing and closing of resource flows within CE models (Ranta et al., 2021). For example, Centobelli et al. (2020) show that Industry 4.0 and other digital technologies have a role in designing business models for CE. They demonstrated how digitalization could improve the monitoring of and control over product data, thus extending its life cycle. This means that digital technologies have positioned themselves as cross-cutting tools that provide a wide range of opportunities in organisations, as extending the life cycle of products is essential to achieving greater efficiency and more responsible consumption.

3 | SAMPLE AND VARIABLES

3.1 | Sample

Our empirical analysis will be performed within the context of digitalization and CE in the EU. The data we use is compiled from two sources (see, e.g., Manea et al., 2021 for a joint use of these two sources) to identify the influence of factors such as the CE and digital innovation in economic and social progress. Regarding CE, our analysis considers the four aforementioned indicators established by the European Commission,[1] previously used in Stanković et al. (2021), to carry out a comparative analysis of the development of CE in Europe. On the digitalization side, we use the Digital Economy and Society Index (DESI), which summarises the most relevant indicators of Europe's digital performance and tracks the evolution of EU Member States (European Commission, 2020). This index has been used in earlier research such as Moreno-Llamas et al. (2020) and Marino and Pariso (2021) to measure, the respective impacts of digital technology development across EU and to evaluate if digital performance is correlated with socio-economic conditions.

From these two sources, we construct a panel that includes a total of 216 observations representing 27 countries[2] across 8 variables for the period 2014–2021. However, the observation window is not the same for the two sources. While the CE database comprises the years 2014[3]–2021, the European Commission began to provide data on DESI in 2016 (European Commission, 2020). This gap in the availability of information poses a dilemma as to which time horizon is the most appropriate to consider. Limiting our analysis to the period in which both databases coincide would substantially reduce the number of observations available.[4] Given the objective of our study and the fact that the implementation of digitalization and CE practices is a

[1]https://ec.europa.eu/eurostat/web/circular-economy/indicators

[2]The countries considered in our research are Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

[3]The information is available from 2014, on the grounds that this is the year in which the EU began actively promote the CE by providing information about its public bodies, private companies and citizens. Furthermore, in 2015 the European Commission adopted the so-called Circular Economy Package (Domenech & Bahn-Walkowiak, 2019).

[4]The overlapping period is limited to the years 2016–2021. Furthermore, one of the four CE variables (competitiveness and innovation) does not provide information for the years 2020 and 2021. Consequently, incorporating it into the analysis would further restrict our observation window.

recent phenomenon, we understand that the availability of current information is particularly relevant. Furthermore, the characteristics of the empirical approach that we propose (we first identify countries with similarities in their circular behaviour; afterwards, we try to explain whether there is a relationship between these groups and the digitalization variables) do not necessarily require that the time period be the same for all the variables under the assumption of short-term country-stability behaviour. As a consequence, while we are aware of the possible biases that this choice may entail, we believe that the advantages of examining a longer period are superior.

3.2 | Approach to the CE

CE is measured taking into account the four areas previously discussed (see Figure 1). Following the approach of studies such as Stanković et al. (2021) and considering the CE's multidimensional nature, there is no defined measurement of the CE's progress; thus, we use the empirical data of the CE framework belonging to official Eurostat databases (European Commission, 2021).

Production and consumption are combined to form an indicator that measures the generation of municipal waste per capita (kg per capita), using annual average population data. Municipal waste includes waste collected and treated by municipal authorities, which is then disposed of through the waste management system. This waste primarily consists of household waste, but it may also include waste from public institutions and small businesses that have been collected by the municipality (European Commission, 2021). Among the different areas of the CE, production and consumption show the poorest performance, particularly in Romania and Poland. However, Denmark, Luxembourg, and Germany stand out as exceptions with better performance in this area. *Waste management* is assessed through the recycling rate of municipal waste. This rate measures the proportion of recycled municipal waste relative to the total waste, calculated by dividing the recycled tonnage by the overall quantity of municipal waste. It encompasses various recycling methods such as material recycling, composting, and anaerobic digestion. Waste management stands as the best performing CE area, having made significant progress in most EU countries. *Secondary raw materials* are approached through the circular material use rate, which measures the share of materials recycled and fed back into the economy—thus saving the extraction of primary raw materials—in overall material use. The secondary raw materials area is relatively underdeveloped except in Belgium and the Netherlands. Moreover, the development of this area is essential if the implementation of a CE is to be achieved and preserve scarce natural resources. Finally, *competitiveness and innovation* are measured through an indicator composed of gross investment in tangible goods and value added at factor costs in CE sectors, expressed in million euros. CE sectors refer to recycling, repairing and reusing sectors (European Commission, 2021). These CE sectors require improvement in all countries due to their low levels, with the exception of Germany, France and Italy, which exhibit higher performance. The assessment of the CE variable is presented in Figure 1, providing an overview of the CE framework.

3.3 | Digitalization variables

Digitalization is measured through four indicators established by DESI on European digital performance: connectivity, human capital, integration of digital technology and digital public services (European Commission, 2020). *Connectivity* represents the percentage of a country's population that is connected to the internet and includes five subdimensions: fixed broadband, mobile broadband, fast broadband, ultrafast broadband and broadband price index. *Human capital* is defined as the percentage of internet user skills and advanced skills. The former is calculated based on the complexity and quantity of activities involving the use of digital devices. The latter refers to indicators related to information technology specialists and graduates. *Integration*

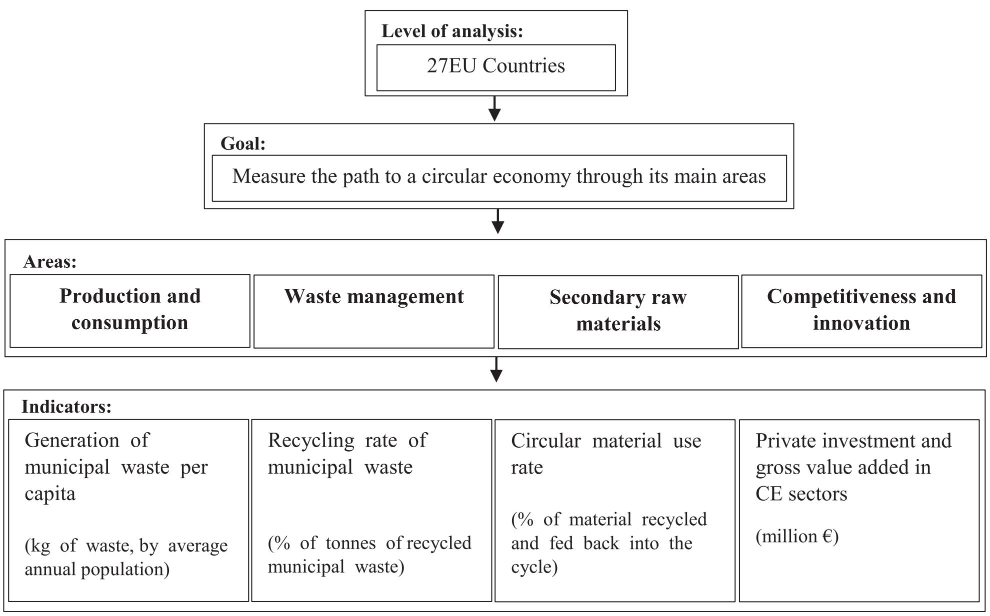

FIGURE 1 Circular economy variables. *Source*: Own elaboration from European Commission (2021).

of digital technology quantify two areas: business digitalization and e-commerce. The first includes initiatives using electronic information sharing, social media use, big data analysis and cloud solutions, whereas the second includes the proportion of small and medium-sized businesses that sell and trade internationally online. Lastly, *digital public services* quantify two weighted dimensions. The first is e-government, quantified by the proportion of online documents submitted, the forms used in government transactions, the public online services available for companies and the level of digital open data sharing. The second is e-health, which measures the rate of health services, the sharing of health records with other health service providers and the prevalence of the e-prescription application. A visual representation of the digitalization variable is presented in Figure 2.

4 | RESULTS

4.1 | Descriptive analysis

Table 1 presents the main descriptive statistics of our key variables. On the one hand, the four CE variables are framed over an 8-year time period, spanning 2014–2021. It is noteworthy that the secondary raw materials CE variable is very low and is indicative of the fact that, on average, less than 9% of all waste generated, collected and recycled in the EU returns to the cycle as new material. At 37% the waste management rate is substantially higher. For production and consumption, the generation of municipal waste per capita is considerably high. Similarly, competitiveness and innovation in terms of private investment and gross value added in CE sectors stands out. A visual approximation of the CE variables by EU countries can be seen in Appendix A, Figure A1. On the other hand, the digitalization variables refer to a 6-year period spanning 2016–2021. Digital public services stand out above the rest, followed by human capital. Behind it, with a similar influence, is connectivity. Lastly, there is integration of digital technology. Additionally, the time dynamics of CE and digitalization variables can be seen in Appendix A, Table A1.

The correlation matrix is shown in Table 2. We observe that three of the four CE areas are positively correlated with the majority of digitalization variables (the exception being competitiveness and innovation) with correlations ranging approximately from 0.30 to 0.50.

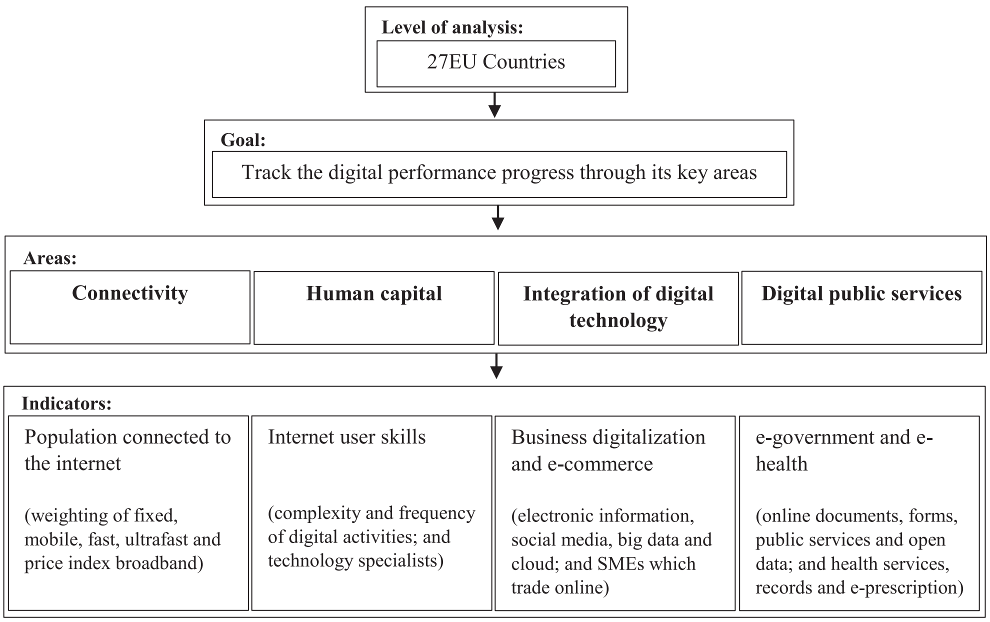

FIGURE 2 Digitalization variables. *Source*: Own elaboration from European Commission (2020).

TABLE 1 Descriptive statistics of the circular economy and digitalization variables ($N = 216$).

Variable	Mean	Std. dev.	Min	Max
Production and consumption	501.76	131.65	247	845
Waste management	37.66	14.71	9.1	71.1
Secondary raw materials	8.89	6.50	1.3	33.8
Competitiveness and innovation	5459.1	8296.6	143.6	37772.6
Connectivity	9.64	2.54	3.84	18.51
Human capital	11.64	2.32	7.38	17.78
Integration of digital technology	7.94	2.50	3.29	14.87
Digital public services	14.36	4.13	2.14	22.94

TABLE 2 Correlation matrix ($N = 216$).

	1	2	3	4	5	6	7	8
1 Production and consumption	1.00							
2 Waste management	0.34***	1.00						
3 Secondary raw materials	0.12*	0.54***	1.00					
4 Competitiveness and innovation	0.30***	0.48***	0.49***	1.00				
5 Connectivity	0.22***	0.22***	0.17**	0.03	1.00			
6 Human capital	0.51***	0.44***	0.28***	0.13	0.46***	1.00		
7 Integration of digital technology	0.47***	0.33***	0.26***	0.04	0.58***	0.79***	1.00	
8 Digital public services	0.51***	0.34***	0.24***	0.13	0.60***	0.74***	0.75***	1.00

Note: In competitiveness and innovation the number of variables is 130 (data for 2020–2021 not available).
*p < 0.05; **p < 0.01; ***p < 0.001.

4.2 | Cluster analysis and analysis of variance

In order to assess the extent to which digitalization has favoured the implementation of the CE at a country level, we first perform a cluster analysis to identify countries exhibiting homogeneous behaviour regarding this dimension (Tokito, 2018). After the cluster analysis, we performed an analysis of variance to compare the different groups (Sthle & Wold, 1989) and to determine whether there are significant differences between them, with the aim of identifying possible patterns that connect digitalization and CE.

4.2.1 | Differences in circular behaviour: Cluster analysis

We start from the four areas previously identified in relation to the level of CE development and combine hierarchical and non-hierarchical methods to achieve the benefits derived from each (Hair et al., 1998). Hierarchical techniques allow us to identify possible outliers, as well as to establish the number of clusters. First, we identify outliers through the single linkage method. The corresponding dendrogram caused us to delete some observations as outliers, reducing the dataset to 23 countries.[5] Afterwards, we normalised the variables and applied the Ward's algorithm with squared Euclidean distance as the similarity measure. This clustering approach resulted in the formation of four distinct groups of countries. Additionally, we apply the results from two stopping rules implemented in Stata to determine the cluster number named Calinski–Harabasz pseudo-F index and the Duda–Hart index. Subsequently, with the aim of adjusting the hierarchical results, the cluster centroids from the Ward method were used as initial seed points for a k-means (non-hierarchical) cluster procedure. Table 4 displays the final cluster solution through the use of the original variable values. As a result, a non-hierarchical cluster analysis with random seeds led to highly similar results. In this way, the stability of the derived solution is demonstrated (Thomä & Bizer, 2013). Moreover, the robustness of the cluster analysis was corroborated by the Kruskal–Wallis test, ascertaining that the average variable values vary significantly across the clusters. The minimum, mean and maximum values for each of the four clusters obtained, which we refer to as *Generators*, *Recyclers*, *Achievers* and *Innovators*, are shown in Table 3.

If we centre on the mean values of the four groups, the first cluster, *Generators*, includes 11 countries (Estonia, Latvia, Portugal, Slovakia, Croatia, Hungary, Cyprus, Poland, Romania, Bulgaria and Greece; 52% of the total sample) that are represented in orange in Figure 3. Their rate of generation of municipal waste (production and consumption) is relatively high; although their score is slightly below the average, it should be noted that the level of consumption (and consequently of waste generation) increases with the income level. Thus, given that income in most of these countries is below the European average, it can be assumed that production and consumption in these countries are likely underestimated given the resources used. Moreover, the remaining three areas are well below average, and are at a very early stage of development. In other words, their recycling rates or their investment in circular activities is comparatively low, making it the group of countries with the lowest level of circularity development. The *Recyclers* group (Cluster 2) includes seven countries (Sweden, Finland, Denmark, Slovenia, Austria, Spain and Lithuania; 25% of the total sample) and is represented in light green in Figure 3. These countries present values close to the mean in production and consumption and in waste management. By contrast, they reach high values in the percentage of recycled materials and in competitiveness and innovation (effort in activities related to circularity). The *Achievers* (Cluster 3), comprises two countries (Belgium and the Netherlands; 9% of the total sample) and is represented in dark green. These countries stand out for their high level in secondary raw materials (their performance is particularly high in this variable, which is almost 70% above the average). Finally, the *Innovators* constitute the Cluster 4 (France, Germany and Italy; 14% of the total sample) and are represented in blue in Figure 3. This group clearly outperforms the average in all four areas. In particular, it is characterised by the highest scores in competitiveness and innovation.

[5] The countries left out of the analysis are Czechia, Ireland, Luxembourg and Malta.

TABLE 3 Descriptive statistics of the clusters ($N = 130$).

		Production and consumption	Waste management	Secondary raw materials	Competitiveness and innovation
Cluster 1: Generators	Min	−1.94	−1.86	−1.17	−0.64
	Mean	−0.64	−0.79	−0.63	−0.46
	Max	1.11	0.23	0.57	0.72
Cluster 2: Recyclers	Min	−0.51	−0.19	−0.77	−0.61
	Mean	0.39	0.78	−0.16	−0.25
	Max	2.60	1.44	0.40	1.01
Cluster 3: Achievers	Min	−0.70	0.90	1.34	−0.33
	Mean	−0.27	1.11	2.28	−0.12
	Max	0.20	1.31	3.25	0.14
Cluster 4: Innovators	Min	−0.12	0.14	0.37	1.45
	Mean	0.39	0.93	1.15	2.25
	Max	1.00	2.01	1.71	3.89
Total	Min	−1.94	−1.86	−1.17	−0.64
	Mean	−0.20	0.02	0.01	2.25
	Max	2.60	2.01	3.25	3.89

Note: Clusters were performed with the mean of the 2014–2021 period.

TABLE 4 Circular economy cluster solution ($N = 130$).

Label	1 ($N = 67$) Generators	2 ($N = 33$) Recyclers	3 ($N = 12$) Achievers	4 ($N = 18$) Innovators	Average Total	df	Chi-square
Production and consumption	−0.64	0.39	−0.27	0.39	−0.20	3	339.03
Waste management	−0.79	0.78	1.11	0.93	0.02	3	375.09*
Secondary raw materials	−0.63	−0.16	2.28	1.15	0.01	3	367.95***
Competitiveness and innovation	−0.46	−0.25	−0.12	2.25	2.25	3	390

Note: Clusters were performed with the mean of the 2014–2021 period.
*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

To summarise, according to the initials of the four identified groups, the cluster analysis is derived from the so-called Generators, Recyclers, Achievers, Innovators (GRAI) classification: *Generators*, countries that stand out in the production and consumption variable, especially when we take into account their level of development; *Recyclers* if they emphasise in secondary raw materials; *Achievers* if they stress on secondary raw materials because these are the ones that achieve the objective of the CE, which is to avoid the use of new natural resources and replace them with secondary raw materials that have been returned to the production cycle; and *Innovators*, who perform particularly well in competitiveness and innovation, although they also perform well in the rest of the variables.

4.2.2 | Analysis of variance

Once the four clusters were identified, an analysis based on variance differences was performed to assess the existence of differences in the digitalization variables in each of the groups. The within-cluster results shown in Table 5 confirm that human capital, integration of digital technology and digital public services are the key drivers that explain the variability in the CE's behaviour carried out by the EU countries. While the analysis does not identify significant differences regarding connectivity, the four groups differ in their levels of human capital and in the integration of digital technologies and digital public services.

Regarding connectivity, we have to bear in mind that our sample solely comprises on EU countries, where connectivity does not generally constitute a barrier to implement the desired circularity initiatives. On the contrary, the implementation of strategies related to sustainability and circularity requires sufficiently qualified staff, which explains why the *Achievers* and *Recyclers* reach higher levels of human capital. Similarly, the implementation of these circularity strategies also requires business digitalization and e-commerce, thus explaining why the *Achievers* accomplish a higher level of integration of digital technology. Lastly, the implementation of circularity strategies necessitates the use of e-government and e-health initiatives. This helps to explain why

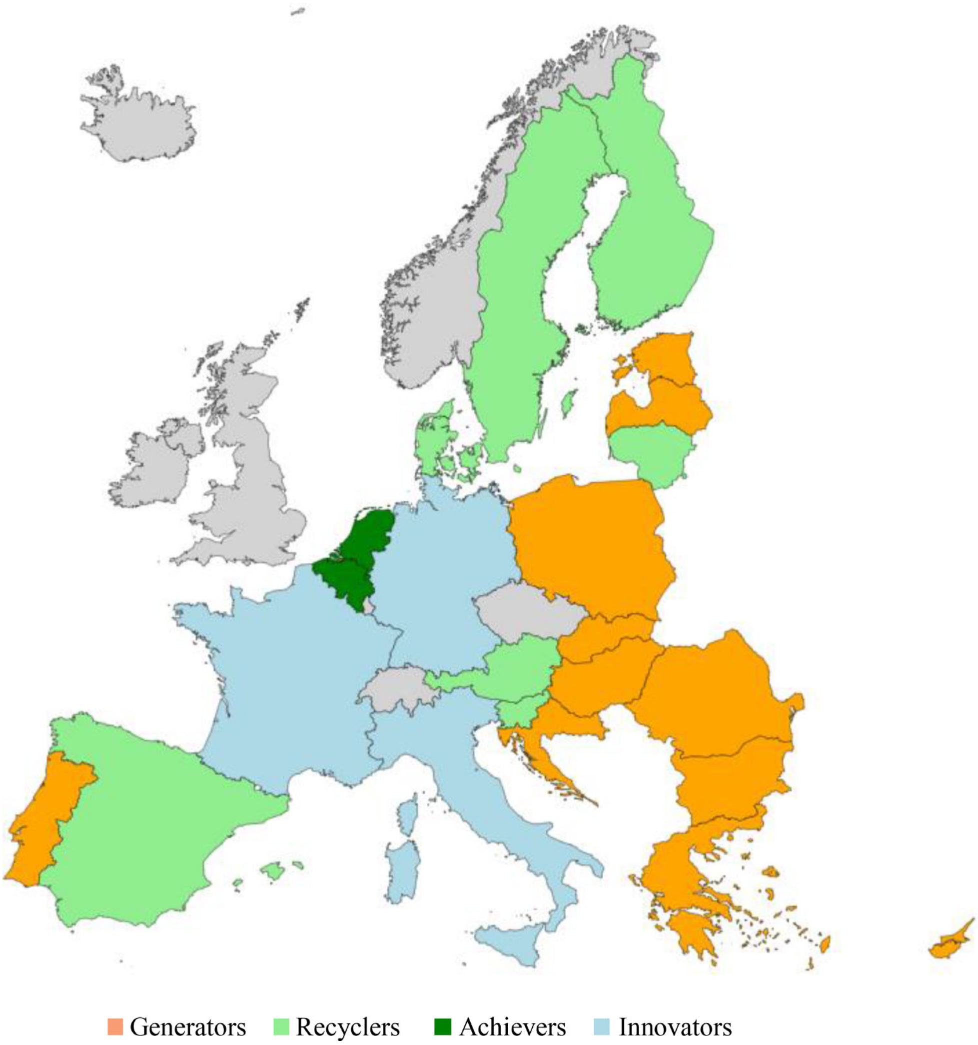

FIGURE 3 GRAI classification cluster map (k-means).

TABLE 5 One-factor analysis of variance (mean and standard deviation).

	Cluster Generators	Recyclers	Achievers	Innovators	*F* value	Chi-square
Connectivity	7.78 (2.00)	9.52 (1.55)	9.24 (1.37)	7.79 (1.42)	6.25***	3.70
Human capital	9.61 (1.32)	13.31 (2.22)	13.20 (1.21)	11.01 (1.99)	28.40***	10.26**
Integration of digital technology	5.40 (1.33)	9.02 (1.66)	9.73 (1.08)	6.57 (0.73)	49.17***	8.54**
Digital public services	10.39 (3.60)	15.89 (2.00)	14.34 (1.89)	12.93 (1.44)	20.49***	18.20***

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

the Recyclers group achieves higher levels of digital public services compared to other groups.

5 | DISCUSSION AND CONCLUSIONS

5.1 | Conclusions

This paper expands a debate that in recent years has received increasing attention in business and public policy, as well as in academia: to what extent digitalization fosters the path towards a CE. The answer to this question is not easy because this debate is in its infancy and thus there is limited information available to analyse it. To face this question, we rely on previous research on digitalization as an enabler of CE performance (Bag et al., 2020; Ingemarsdotter et al., 2020), as well as on studies that show that digitalization can favour the implementation of CE (Getor et al., 2020). With this aim in mind, we follow a two-step procedure. First, we characterise different groups of EU countries according to their CE performance, as derived from the so-called GRAI classification. Regarding the first step, the best positioned countries are the *Achievers* (Belgium and the Netherlands) and the *Innovators* (France, Germany and Italy). The *Generators* (Estonia, Latvia, Portugal, Slovakia, Croatia, Hungary, Cyprus, Poland, Romania, Bulgaria and Greece) need to improve considerably in all areas, while the *Recyclers* (Sweden, Finland, Denmark, Slovenia, Austria, Spain and Lithuania) are in an intermediate position.

We have confirmed that the countries that stand out in CE practices are those that score high in secondary raw materials and in competitiveness and innovation. In particular, the extant literature has evidenced that the development of secondary raw materials seems to be vital in the context of this issue (Mazzarano, 2022), being the CE variable that comes closest to the full scope of the CE since recycled materials replace newly extracted natural resources, reducing the environmental footprint. Likewise, in line with the results obtained by Suchek et al. (2021) the countries with a better CE performance are those that score higher in competitiveness and innovation. The more resources invested in CE activities and the greater the employment in these areas, the more companies will improve the design of their products to facilitate their reuse and, at the same time, the promotion of innovative industrial processes (Cillo et al., 2019). This could lead to simultaneous self-sufficiency in certain raw materials. On this basis, the CE field needs to gain momentum as it will act as a driving force to sustainable development.

Regarding digitalization, we have observed that there is a relationship between the circular behaviour of EU countries and certain digitalization dimensions. More precisely, human capital, the integration of digital technologies within the companies and the digital public services favours the implementation of circular strategies. In particular, the more advanced countries are in relation to the implementation of CE practices, the ones that our proposed classification has labelled as *Achievers*, as well as *Recyclers*, are more likely to possess highly qualified human capital (higher skills in the use of the internet). Likewise, *Achievers* are able to accomplish a higher level of business digitalization and e-commerce and *Recyclers* a higher level of e-government and e-health. Consequently, while our model does not establish a direct causal relationship between the variables examined, our preliminary evidence suggests that certain factors are prerequisites for the successful implementation of CE policies in a country. These include improving the digital skills of the population, enabling companies to integrate digital technologies into their operations, and facilitating digital transformation in government processes. In this way, digitalization could be considered the cornerstone for countries to reach the standards required to move from a linear economy to a CE.

5.2 | Policy and business implications

Our results lead to some suggestions that may be of interest both from a policy point of view and for business practice. Regarding the former, it seems clear that public authorities are aware of the problems suggesting there exists a scarcity of natural resources, whilst their demand is simultaneously increasing. Therefore, the involvement of public institutions is crucial to encourage the design of policies and incentives oriented towards effective recycling in order to achieve quality in waste management (Kazancoglu et al., 2021), which will be necessary to convert a high proportion of recycled waste into secondary raw materials. Nevertheless, to achieve the highest levels of circularity, policymakers should not forget to emphasise the importance of recycling as much waste as possible. Additionally, it would be necessary to enforce the transposition of the European CE directives of waste generation at the country level, to provide an impetus in the road to sustainability, especially in those countries where the CE is at a more incipient stage, as in the case of the *Generators*. However, even if material recovery is accepted as an institutionally imposed objective, a number of financial, institutional and information barriers need to be overcome, such as the high cost of EC implementation, the lack of legislative harmonisation of European directives or the shortage of technical competences, knowledge and skills (Grafström & Aasma, 2021; Ranta et al., 2018). In the same way, digital human capital, integration of digital technology and digital public services, as key drivers of variability in the CE, should be encouraged by public authorities. This, in turn, may result in improved efficiency, convenience and cost savings because digitising public services can significantly reduce operational costs for institutions (Uyar et al., 2021). Moreover, the improvement of digital human capital and integration of digital technology can provide an opportunity to bridge the digital divide and make public services accessible to a wider population, as well as an improvement in transparency and accountability in public service delivery.

Concerning business implications, companies should be proactive in adopting CE practices. It is clear that strategy formulation increasingly requires the incorporation of social and environmental issues and that, through the incorporation of digitalization and CE practices, companies are moving in the right direction (Elkington & Rowlands, 1999; Wagner et al., 2002). In this way, they will be able to improve the quality and sustainability of the products they deliver (Ciliberto et al., 2021). At the same time, an environmentally committed organisation would attract the best talent (Yong et al., 2020), which may make it easier for companies to align their business strategies with the needs of the environment. Finally, a proactive approach to the CE will make companies more competitive through the development of capabilities (Sharma & Vredenburg, 1998), which will be decisive in a dynamic environment. Any effort in this direction will result in higher levels of innovation, which at the same time is deemed instrumental to achieving a sustainable transition (Kiefer et al., 2021; Sehnem et al., 2021).

5.3 | Limitations and future research

This study is not without its limitations, which deserve further attention in subsequent work. First, our analysis focuses on EU countries, whose characteristics and level of development are different from that of other countries around the world. Thus, it would be of interest to verify whether these results remain consistent in other contexts. Second, it is important to note that the available information on digitalization and CE variables is still limited, and obtaining more detailed data in these areas would further enhance the robustness of our results. Additionally, as mentioned earlier, the public information used in our analysis comes from different time periods, which introduces some limitations to our analysis. We acknowledge that our decision to utilise all the available years in each data series, despite the resulting heterogeneity in the time horizon, was not without risks. However, we believe that it was the best approach to avoid significant data loss. In the future, as longer and more consistent data series become available, it will be possible to achieve greater homogeneity and strengthen the quality of the results. Nevertheless, it should be noted that a longer time horizon could result in heterogeneous evolution of countries' behaviour, potentially influencing the composition of country groups. Given our predominantly static approach, we have not explicitly taken this aspect into consideration; therefore, it should be recognised as an area for further investigation in future research. Third, our data, and in particular, the digitalization variables, would benefit from being analysed in a more disaggregated and detailed manner. In this sense, future studies could be carried out the study of differences between clusters in terms of digitization characteristics. Fourth, this study has adopted a macro approach, with an analysis at the country level; when the availability of the information allows researchers to do so, it would be of interest to complement it with an analysis at the firm level.

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ORCID

Mercedes Gil-Lamata https://orcid.org/0000-0002-1816-5394
Lucio Fuentelsaz https://orcid.org/0000-0002-9002-6727
María Pilar Latorre-Martínez https://orcid.org/0000-0002-8486-6885

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APPENDIX A

Figure A1 displays the CE variable's mean from 2015 to 2020, by means of its four main areas. Green indicates high values, which is very favourable for the CE. In this regard, the best performing CE area is waste management. Yellow and orange show the average values. These colours rule in production and consumption, all being the countries in said colours, with the exception of Denmark, Luxembourg and Germany with the highest values, and Romania and, Poland with the lowest. By contrast, the smallest variable values are in red, which indicates that there is still a long way to go for the implementation of a CE system in EU countries. Those colours prevail in the secondary raw materials and competitiveness and innovation in all countries except for France, Italy and Germany; particularly in the latter, which demonstrates the worst performance. Consequently, the area referring to secondary raw materials, which concerns the share of materials recycled and fed back into the economy—thereby saving the extraction of primary raw materials—must be further developed if the implementation of a CE is to be achieved and preserve scarce natural resources. It is also clear that the area of competitiveness and innovation needs to be improved as it is fundamental to the development of the new business model.

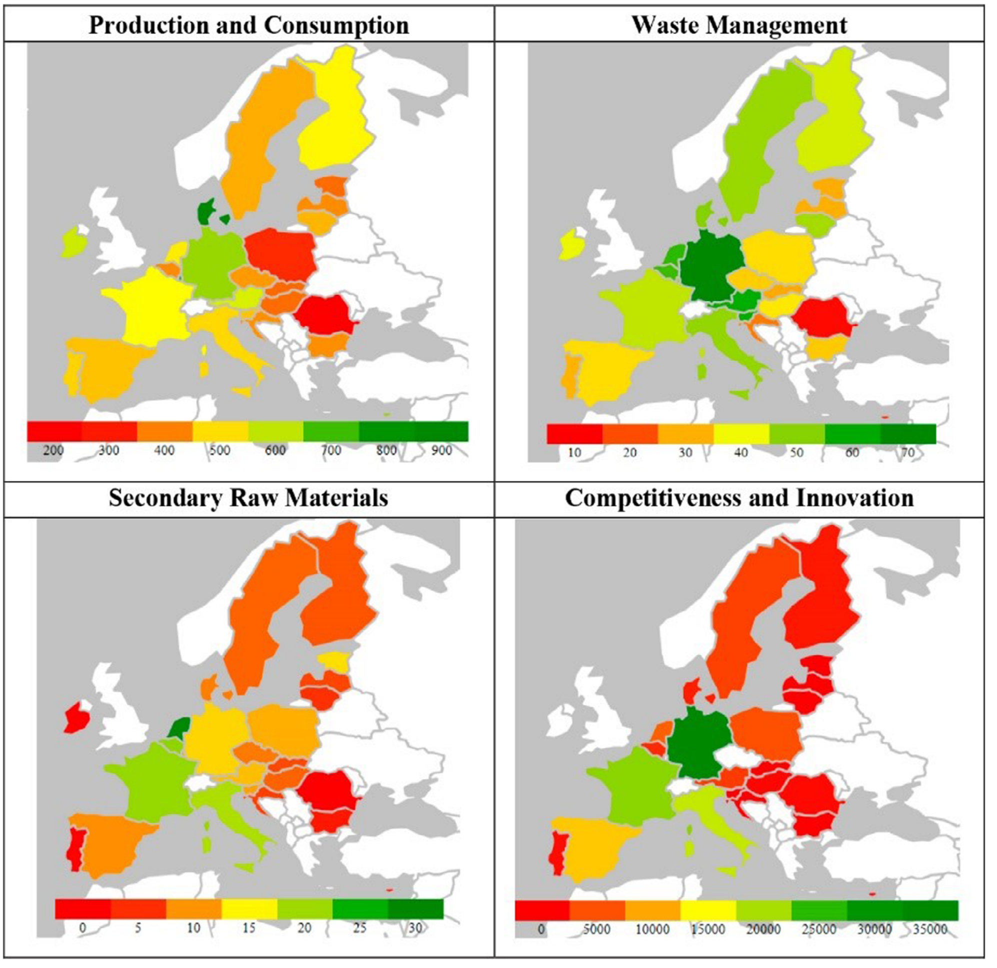

FIGURE A1 Circular economy variables heat map (mean over 2015–2020).

Table A1 illustrates the temporal dynamics of the CE and digitalization variables. Over the period from 2014 to 2021, the CE variables have shown consistent growth since the beginning of the period, with the exception of a decrease in their values in 2021. Among the CE variables, the secondary raw materials variable exhibits the slowest growth throughout the period. On the other hand, the digitalization variables have experienced progressive increases from 2016 to 2021. Of particular note is the substantial growth observed in connectivity and digital public services. However, the variable representing human capital has only shown a minimal increase of 1% over the entire period, indicating slower progress in this area compared to the other digitalization variables.

TABLE A1 Year-evolution of the descriptive statistics of the study variables ($N = 216$).

	Year	Mean	Std. dev.	Min	Max
Production and consumption	2014	468.30	125.87	249	808
	2015	469.23	126.62	247	822
	2016	488.89	137.35	261	830
	2017	499.78	127.81	272	820
	2018	505.85	126.98	272	814
	2019	514.81	129.03	280	844
	2020	539.04	145.33	290	845
	2021	534.36	132.70	302	793
Waste management	2014	33.18	14.82	10.3	65.6
	2015	35.16	15.20	10.9	66.7
	2016	37.26	14.69	12.7	67.1
	2017	37.75	14.53	11.5	67.2
	2018	38.3	14.97	10.4	67.1
	2019	39.6	14.57	9.1	66.7
	2020	40.54	14.51	10.9	70.3
	2021	39.93	14.98	11.3	71.1
Secondary raw materials	2014	8.25	5.95	1.4	26.6
	2015	8.21	5.97	1.7	25.8
	2016	8.39	6.30	1.7	28.5
	2017	8.78	6.48	1.7	29.7
	2018	9.01	6.60	1.5	28.9
	2019	9.47	7.10	1.3	30
	2020	9.71	6.82	1.5	30
	2021	9.32	7.33	1.4	33.8
Competitiveness and innovation	2014	5184.60	7831.21	241.4	28362.8
	2015	5017.94	7743.59	143.6	28628.4
	2016	4930.45	7869.71	162.1	31246.3
	2017	5498.21	8429.53	19,739	32080.3
	2018	5898.89	9074.59	220.9	34799.8
	2019	6294.3	9646.16	244.7	37772.6
Connectivity	2016	7.40	1.84	3.84	10.74
	2017	8.19	1.67	4.62	11.14
	2018	8.87	1.66	5.10	11.62
	2019	9.66	1.63	5.93	12.42
	2020	10.96	1.85	6.91	13.71
	2021	12.79	2.19	9.43	18.51
Human capital	2016	11.13	2.25	7.38	16.38
	2017	11.28	2.28	7.42	16.33
	2018	11.59	2.34	7.50	16.78
	2019	11.74	2.33	7.56	16.50
	2020	11.97	2.38	7.91	17.13
	2021	12.12	2.42	8.18	17.78

TABLE A1 (Continued)

	Year	Mean	Std. dev.	Min	Max
Integration of digital technology	2016	6.18	1.80	3.29	9.35
	2017	6.94	1.98	3.76	10.49
	2018	7.63	2.07	4.22	11.77
	2019	8.29	2.26	4.53	12.69
	2020	8.86	2.45	4.83	13.90
	2021	9.75	2.71	5.12	14.87
Digital public services	2016	11.87	3.45	2.14	16.98
	2017	12.76	3.58	2.57	17.81
	2018	13.84	3.75	3.18	19.14
	2019	14.73	3.84	3.68	20.21
	2020	15.83	3.96	4.50	21.49
	2021	17.13	4.09	5.37	22.94