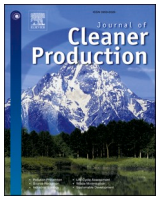
Journal of Cleaner Production 425 (2023) 138759

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



A global and comparative assessment of the level of economic circularity in the EU

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ARTICLE INFO

Handling editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Circular economy
Circular economy composite index
Principal component analysis
Circular transition
Circular economic ranking
EU circular plan

ABSTRACT

The European Union (EU) stands as one of the pioneering areas worldwide in the planning of the Circular Economy (CE), despite the fact that practical advances in this area are currently ahead of the related research. Significant gaps remain to be filled, particularly with regard to the measurement of circularity. This work is based on the need for global tools to measure the circular transition which, in turn, can be useful in evaluating the implementation of the action plans under development by the EU.

A composite index of economic circularity (CECI) has been built for the EU and its Member States with which to approximate the progress after completion of the first Action Plan for the Circular Economy (APCE): 2014–2020. This index is based on recycling and downcycling, which is the main strategy developed by APCE. In contrast to previous indicators, CECI globally and rigorously summarises the transition towards the circular economy throughout the period of validity of the plan, by using a simple and easy-to-interpret calculation methodology known as Principal Component Analysis. Likewise, the results of the CECI make it possible to establish a ranking of the EU Member States based on their CE performances for each year under consideration. The results of the CECI show that the EU as a whole has advanced in economic circularity by 17.9%, which is almost 3% on average per year. The situation is very uneven across the various Member States and, although differences have narrowed during the APCE period, in recent years this rapprochement has deaccelerated. The countries that continue to lead the circular transition of the EU are the Netherlands, Belgium, and Germany, while trailing behind are Romania, Malta, and Cyprus. In light of the results of the CECI and with the aim of achieving greater convergence in the transition to economic circularity in the EU, it would be advisable to intensify actions in those Member States whose starting situation is comparatively worse.

1. Introduction

The climate emergency has highlighted the urgency for change in the economic model that allows competitiveness to be combined with environmental and social objectives (Bluszcz, 2018; Ellen MacArthur Foundation, 2012; Galiano Bastarrica et al., 2023). Over the last decade, the Circular Economy (CE) has begun to be considered as a viable alternative for such a change of model (European Commission, 2019). According to Bourguignon, 2016: 2, CE is an Economic Model based "on sharing, leasing, reuse, repair, refurbishment and recycling, in an (almost) closed loop, which aims to retain the highest utility and value of products, components, and materials at all times". The European Union (EU) estimates that circular transition will enable climate neutrality to be achieved by 2050, by decoupling economic growth from the excessive use of resources. This transition will also reduce external dependence on both energy and basic raw materials, thereby promoting a greater security of supply and reducing price volatility (European Commission, 2020a). The former is especially relevant given the supply problems experienced during the Covid-19 pandemic and as a result of the current conflict in Ukraine. However, the CE is not without its limitations and criticisms, since not all CE actions are environmentally or socially sustainable (Blum et al., 2020; Corvellec et al., 2021; Geissdoerfer et al., 2017). There are many circular futures, not all of which have to be sustainable.

In order to promote circular transition, in 2015 the EU launched their

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https://doi.org/10.1016/j.jclepro.2023.138759
Received 7 July 2023; Received in revised form 28 August 2023; Accepted 8 September 2023
Available online 18 September 2023

Abbreviations

APCE	Action Plan for the Circular Economy (first EU Plan)
CE	Circular Economy
CEAP	Circular Economy Action Plan (current EU Plan)
CECI	Circular Economy Composite Index
CMUR	Circular Material Use Rate
MFCE	First Monitoring Framework on Circular Economy of EU
PCA	Principal Component Analysis
RB	Recycling Rate of Biowaste
RMW	Recycling Rate of Municipal Waste
ROP	Recycling Rate of Overall Packaging

first Action Plan for the Circular Economy (APCE) (European Commission, 2015) for a time horizon of 5 years, whose actions focused primarily on the strategy of the preservation of materials through recycling and downcycling[1] (Moraga et al., 2019). On completion of its implementation, a new Circular Economy Action Plan (CEAP) is under development, which is focused on achieving "a cleaner and more competitive Europe" (European Commission, 2020a).

Similar to the EU, many countries are committed to the CE. China constituted not only one of the pioneers, but also a reference for the EU (European Commission, 2005). Currently, China has established strong policies at the macro and mesoeconomic level, contributing decoupling in the use of resources from GDP growth as well as industrial decarbonisation (Bleischwitz, et al., 2022). It is also worth noting the case of Canada, which, although still in the initial stages and the pressure to establish specific strategies, is demonstrating a growing commitment (Gagnon et al., 2022). On the other hand, the governments of several countries (including Canada, Chile, Colombia, Ecuador, India, and the EU), have formed The Global Alliance on Circular Economy and Resource Efficiency (GACERE) with the intention of achieving a just and sustainable transition towards the Circular Economy.

The scientific literature on Circular Economy has grown considerably (Arsova et al., 2022; Kirchherr et al., 2023; Lozano et al., 2021), having made advances both in conceptualisation and modelling (Campbell-Johnston et al., 2020; Kirchherr et al., 2017, 2023; Lozano et al., 2021; Momete, 2020) and in the proposal of strategies and specific measures for its implementation (Cramer, 2022; Dagilienė et al., 2021; Kalmykova et al., 2018). However, no commonly accepted framework has yet been established for the measurement of economic circularity (Bianchi et al., 2023; Corvellec et al., 2022; Elia et al., 2017; De Pascale et al., 2021; Parchomenko et al., 2019; Saidani et al., 2019; Silvestri et al., 2020; Stanković et al., 2021), which makes it difficult to monitor and evaluate not only action plans, but also the approach of new proposals.

A large proportion of the studies on Circular Economy measurement considers one-dimensional partial indicators (those that only offer a part of the information of a global system, concept, or reality) for the quantification of various aspects of circularity (De Pascale et al., 2021; Parchomenko et al., 2019; Sassanelli et al., 2019), but they fail to embody the multidisciplinary and systemic character of the Circular Economy (Bianchi et al., 2023; Saidani et al., 2019). In order to overcome this problem, several authors and institutions have developed Circular Economy-monitoring frameworks that group various one-dimensional indicators based on their specific objectives (Elia et al., 2017; European Commission, 2018; Momete, 2020; Sassanelli et al., 2019; Thakker and Bakshi, 2021). In this respect, the Monitoring Framework on Circular Economy (MFCE) is of note, designed by the European Commission (2018) in order to assess the transition towards circularity in the EU. This framework, despite capturing the multi-dimensional character of the Circular Economy, fails to offer any index that globally summarises the achievements in this area (Garcia-Bernabeu et al., 2020). As pointed out by the OECD (2008), since composite indices are easily interpretable and make rankings possible, they can provide useful tools for decision-making, policy monitoring, and a means of communication to the public.

Thus, the lack of composite indices constitutes one of the main shortcomings in the literature on Circular Economy measurement (Sassanelli et al., 2019). Although several studies have been published at the European level that propose composite indices, these are insufficient in the assessment of the circular transition after the full implementation of CEAP either due to lacking information from all countries (Karman and Pawłowski, 2022; Kasztelan, 2020; Mitrovic and Milan, 2018; Silvestri et al., 2020), or because they are insufficiently updated (Ailincă et al., 2022; Busu and Busu, 2018; Garcia-Bernabeu et al., 2020; Kasztelan, 2020; Mitrovic and Milan, 2018; Silvestri et al., 2020; Stanković et al., 2021), or due to their use of complex calculation methodologies and/or their inclusion of redundant information (Garcia-Bernabeu et al., 2020). In this respect, as stated by Fellner and Lederer 2020: 319, "the metrics for measuring and assessing the transition towards a circular economy have proven to be most successful if they can be calculated and communicated in a straightforward and simple manner".

This work aims to contribute towards overcoming these shortcomings. The following objectives are therefore set: (1) to build a composite index that enables the advances in economic circularity in the EU derived from APCE to be quantified at a macro level and in a global, simple, and representative way, taking as reference the first MFCE proposed by the European Commission in 2018 for the monitoring and evaluation of the APCE; (2) to assess the achievements of the EU and its Member States in terms of circularity subsequent to the implementation of said Plan.

In order to achieve these objectives, the construction of a Circular Economy Composite Index (CECI) is proposed, principally based on recycling and downcycling, and is updated for all Member States, for which the following methodological strategy is employed. Once the territorial scope and the time frame have been delimited, the one-dimensional indicators are selected based on both the literature review and the institutional framework of the EU. Thus, those direct one-dimensional indicators of the first MFCE that are linked to the main Circular Economy strategies developed in APCE are chosen, while avoiding repetitions. By utilising Principal Component Analysis as the aggregation and weighting methodology for the selected one-dimensional indicators, the CECI is calculated, and rankings are established based on the results for the Member States. Finally, the evolution of the EU and its Member States from 2014 to 2020 is analysed by carrying out two types of analysis: static (countries with the best behaviour); and dynamic (countries that have advanced the most).

The contribution of this work is twofold. On the one hand, it enriches the existing literature by covering the gap regarding the measurement of economic circularity. To the best of our knowledge, this is the first work that builds a Circular Economy Composite Index for the current 27 Member States and the UK that is up-to-date, simple, intuitive, realistic, and representative of the actions included in APCE. On the other hand, the results achieved could be relevant for the EU policy-makers by expanding the tools that enable the progress in the transition towards circularity to be monitored subsequent to the implementation of APCE. Specifically, the CECI can be especially useful both for decision-making regarding future actions and for transmitting the results to the population.

The paper is structured as follows: the following section includes a review of the literature on the conceptual and institutional framework of the Circular Economy and its measurement; Section 3 details the

[1] According to Mugdal et al. (2011), *recycling* is a process by which end-of-life waste is converted into materials capable of being used for a purpose similar to the original; while *downcycling* is recycling process in which the material quality decreases due to its impurity caused by mixing, poor separation, and misclassification.

methodology and data used; Section 4 is dedicated to the analysis of the results and their discussion; and finally, the conclusions are presented.

2. Literature review

2.1. Circular economy: conceptualisation and institutional framework in the EU

Ever since Boulding (1966) pointed out the need to adopt a closed system that would take into account the limited resources of the planet, the presence of the Circular Economy in the scientific literature has been gaining momentum, and has become a fashionable topic (Arsova et al., 2022; Corvellec et al., 2022 Kirchherr et al., 2017, 2023; Lozano et al., 2021). However, no widely agreed definition has yet been established (García-Barragán et al., 2019; Corvellec et al., 2022; Korhonen et al., 2018a, b; Silvestri et al., 2020), which is mainly due to the complexity of the term (Rizos et al., 2017). Indeed, Blomsma and Brennan (2017) referred to the Circular Economy as an umbrella concept that encompasses a series of inter-related pre-existing terms.

Kirchherr et al. (2023: 4), proposed one globalised definition after having analysed 221 definitions: "The circular economy is a regenerative economic system which necessitates a paradigm shift to replace the 'end of life' concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities".

Although knowledge regarding the Circular Economy has undergone marked and consolidated development since 2017 (Kirchherr et al., 2023), certain authors consider it impossible to achieve a single definition of the Circular Economy (e.g., Korhonen et al., 2018a, b) and hence they prefer to focus on the principles and strategies behind the concept. The Circular Economy principles are linked to the so-called Rs, ranging from the popular 3Rs (reduce, recycle, and reuse) to the more extensive approach of Potting et al. (2018), which indicates up to 10Rs (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover).

These principles can be identified in the increasingly frequent circularity strategies that are being proposed and developed, in which China and the EU are pioneers. The scientific literature has made major efforts to classify and systematise circularity strategies, with special emphasis on the proposals of Potting et al. (2018) and Moraga et al. (2019). Potting et al. (2018) group these principals in terms of priority into three categories: 1) manufacture and use of smarter products (refuse, rethink and reduce); 2) extension of the useful life of products and components (re-use, repair, refurbish, remanufacture, and repurpose); and 3) useful applications of materials (recycle and recover). Starting from the previous hierarchical classification, Moraga et al. (2019) identify six groups of strategies as summarised in Table 1. The first five are based on preservation (of functions, products, components, materials, and energy) while the last group considers strategies linked to the reference scenario.

Table 1
Moraga et al. (2019) Circular economy strategies.

- *Strategy 1.* Preserve the **function** of products or services provided by circular business models.
- *Strategy 2.* Preserve the **product** itself.
- *Strategy 3.* Preserve the **product's components.**
- *Strategy 4.* Preserve the **materials** through recycling and downcycling.
- *Strategy 5.* Preserve the embodied **energy.**
- *Strategy 6.* Measure the **linear economy** as the **reference scenario** or the **absence of a preservation.**

Source: Adapted from Moraga et al. (2019, p. 454)

The EU, aware of the urgency of circular transition and of the need to be able to rely on the necessary institutional support to make it possible, has assumed a significant role in the last decade that we have summarised in 10 types of actions.

1. Prioritise the transition to Circular Economy within its strategic objectives (European Green Deal, European Commission, 2019)
2. Plan the necessary actions to achieve this transition (APCE: EU Action Plan for the Circular Economy "Closing the loop"; and CEAP: A New Circular Economy Action Plan "For a cleaner and more competitive Europe", European Commission, 2015, 2020a)
3. Regulate Circular Economy actions (European Parliament and Council, 2018a, 2018b, 2018c)
4. Promote certifications and labels (see www.ecolabel.eu, European Commission, 2023a)
5. Promote and make good practices visible (European Circular Economy Stakeholder Platform for Good practices,European Union, 2022)
6. Develop awareness and training campaigns (e.g., European Skills Agenda, European Commission, 2020b)
7. Promote R&D&i linked to the Circular Economy (e.g., Horizon Europe-Cluster 6. Destination 3: Circular Economy and Bioeconomy Sectors)
8. Develop statistics and reports (through the specific section for the Circular Economy of Eurostat or the Monitoring Framework for the Circular Economy, European Commission, 2018, 2023b)
9. Provide financial support (Multiannual Financial Frameworks, MFF, 2014–2020, European Union, 2013; MFF, 2021–2027, European Union, 2020; and Next Generation Package, European Commission, 2020c)
10. Impose tax on contrary practices (new revenue source for the 2021–2027 EU budget based on the non-recycled plastic packaging waste)

This institutional framework for the Circular Economy in the EU can be structured into two periods that coincide with the timeframe of the two Circular Economy Action Plans (2015-19 and 2020-24). Our focus is on the analysis of the first plan since the second is still under development and hence it is not yet possible to assess its results. Fifty-four specific measures were included in APCE (European Commission, 2015) for their development over 5 years, which focused on 5 priority areas (plastics, food waste, critical raw materials, construction/demolition, and biomass). Although the plan included measures related to all stages of the product life cycle, the majority have focused primarily on the last stage of the linear process, through waste management, recycling, and reuse (Hartley et al., 2020:1), which is more specifically indicated in Moraga et al. (2019) as *Strategy 4. Preserve the materials through recycling and downcycling.*

2.2. Circular economy measurement in the EU

In order to assess the implementation of the circular model, it is necessary to have suitable indicators. Although there is a large number and variety of sustainability indicators widely accepted by the scientific community, the specific measurement of the Circular Economy remains in its infancy (Elia et al., 2017; Saidani et al., 2019; Silvestri et al., 2020), which may be due to the ambiguity and lack of consensus in its aforementioned conceptualisation (de Oliveira and Oliveira, 2023; Parchomenko et al., 2019).

Recent reviews of the literature (De Pascale et al., 2021; Parchomenko et al., 2019; Sassanelli et al., 2019) show the existence of numerous one-dimensional partial indicators that can be utilised to quantify specific aspects of the Circular Economy, but they also note deficiencies in the overall measurement of the Circular Economy (de Oliveira and Oliveira, 2023). These studies classify the partial Circular Economy indicators by considering different criteria. Depending on the

scope of application, three categories of indicators are distinguished (De Pascale et al., 2021): macro-level (country/region, province, municipal); meso-level (industry); and micro-level (enterprises, clients, products). Other classifications group the indicators according to the Circular Economy strategy or principle to which they are linked (Elia et al., 2017; Saidani et al., 2019) or to whether the measurement of circularity is carried out directly or indirectly (Moraga et al., 2019).

The main criticism of these partial Circular Economy indicators is that they do not embody the multidisciplinary and systemic character of the Circular Economy (Saidani et al., 2019). To overcome this shortcoming, Circular Economy monitoring frameworks are proposed that group various one-dimensional indicators according to the objectives they pursue (Elia et al., 2017; European Commission, 2018; Momete, 2020; Sassanelli et al., 2019; Thakker and Bakshi, 2021). In this respect, we point to the first MFCE proposed by the European Commission in 2018 for the monitoring and evaluation of the APCE. The MFCE proposes 22 indicators/sub-indicators grouped into 4 categories: production and consumption, waste management, secondary raw materials, and competitiveness and innovation. Moraga et al. (2019) makes an interesting classification of these indicators based on the type of Circular Economy strategy with which they can be linked (see Table 1) and their direct or indirect nature. They conclude that, consistent with the type of measures of the Circular Economy Plan, most of the indicators are linked to Strategy 4, which is related to the preservation of the materials. Among the limitations of the MFCE, the lack of data for certain indicators has been pointed out, especially for the group of production and consumption, together with the lack of a homogeneous update. Moreover, this monitoring framework does not include a global indicator that summarises the circularity status of the EU (Garcia-Bernabeu et al., 2020).

The lack of composite indices is one of the main shortcomings in the literature on Circular Economy measurement (Sassanelli et al., 2019). Composite indices are aggregating measures that, by summarising complex information, are useful for decision-making, are easily interpretable, and facilitate rankings, policy monitoring, and communication to the public (OECD, 2008).

After reviewing the literature, we have found only 8 studies that have built Circular Economy composite indices at a macro level for the EU and its Member States. These indices are very different from each other both in terms of the number and type of one-dimensional partial indicator considered, and in relation to the methodology used, or the spatial and temporal scope considered (see Table 2 in which benchmarking of the Circular Economy composite indices for the EU has been carried out).

The time horizon of the majority of these composite indices is 2016, which makes it impossible to assess the progress made by APCE. Furthermore, only 4 of these indices are calculated for all Member States of the EU (Ailincă et al., 2022; Busu and Busu, 2018; Garcia-Bernabeu et al., 2020; Stanković et al., 2021). The composite indices analysed use a large number of partial indicators, including, in certain cases, information that could be considered redundant (Garcia-Bernabeu et al., 2020). Most of these partial indicators are based on the MFCE and combine partial indicators from the 4 groups into which this monitoring framework is structured. Regarding the weighting and/or aggregation methodology used, the studies that use different multi-criteria techniques stand out (Garcia-Bernabeu et al., 2020; Kasztelan, 2020; Stanković et al., 2021) as do those that use PCA to reduce the dimensions and assign weights (Karman and Pawłowski, 2022; Stanković et al., 2021). As Karman and Pawłowski (2022) point out, one of the weaknesses of these global Circular Economy metrics is their high computational complexity, which can cause them to lose part of their initial purpose (i.e., to communicate directly and simply).

From the review of the literature, it can be concluded that, to the best of our knowledge, there is no Circular Economy composite index at a macro level that enables a global and simple assessment of the circular transition of the EU and its Member States derived from the implementation of APCE and that, in addition, it is capable of transmitting the advances in circularity to European citizens in a rigorous and intuitive way. Furthermore, no other research has been found that measures circularity until 2020 and fully covers APCE.

Table 2
Benchmarking of the Circular Economy composite indices for the EU.

Reference	Partial indicators (Based or not on MFCE[1])	Geographical scope	Timeline	Methodology
Busu and Busu (2018)	2 (not MFCE)	UE-27 + UK	2007–2016	Shannon Entropy
Mitrovic and Milan (2018)	11 (MFCE)	UE-23	2016	Data Envelopment Analysis
Garcia-Bernabeu et al. (2020)	17 (MFCE)	UE-27 + UK	2016	Multi-criteria (TOPSIS)
Kasztelan (2020)	14 (MFCE)	UE-23 + UK	2016	Multi-criteria (Taxonomic linear ordering method)
Silvestri et al. (2020)	11 (not MFCE)	169 NUTS2	2015	Circular Economy dimensions have the same weight
Stanković et al. (2021)	11 (MFCE)	UE-27 + UK	2010–2016	PCA and Multi-criteria (Promethee)
Karman and Pawłowski (2022)	30 (not MFCE)	UE-24 + UK	2019	PCA and Catastrophe progression method
Ailincă et al. (2022)	9 (MFCE)	UE-27	2009–2019	Arithmetic mean.

Note: [1] First Monitoring Framework on Circular Economy of EU.
Source: Authors' own

3. Material and methods

In order to assess the transition towards economic circularity in the EU and its Member States within the existing institutional framework, we propose a composite index, the CECI. For its construction, a methodological approach has been followed through several stages (See Fig. 1).

First, the *geographical scope* and the *time frame* are selected. The CECI is then calculated for the EU, its 27 Member States, and the UK, for four years: for 2014, the year prior to the publication of APCE; for 2018, the year of publication of the first MFCE; for 2019, the last year for which other authors have indices, which enables comparisons to be made; and 2020, the latest year with updated information and the first year after its program, thereby enabling the evaluation of the Circular Economy evolution during the entire period of the validity of the APCE.

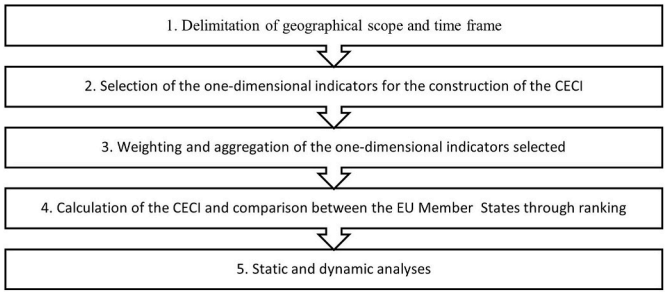

Fig. 1. Stages of research.
Source: Authors' own

The *selection of the indicators* for the construction of the CECI has been carried out based on the review of the literature and on the institutional framework of the EU and is in accordance with the following criteria. As shown in Table 3, it is based on the set of indicators included in the MFCE since it was explicitly designed for the monitoring and evaluation of APCE. Moreover, the MFCE utilises information from Eurostat, which guarantees high-level quality standards of European Statistics. Of the 22 indicators/sub-indicators of the MFCE, those for which there is still no information available for any country are discarded [1. EU self-sufficiency for raw materials, 7.1. End-of-life recycling input rates (EOL-RIR), aluminium (%)], and those which were not up to date for any country at the date of the investigation for the year 2020 have also been discarded. (3.2. Generation of waste excluding major mineral waste, 5.2. Recycling rate of all waste excluding, 6.4. Recycling rate of e-waste, 6.6. Recovery rate of construction and demolition waste).

In order to achieve a significant, simple index that eschews duplication of information, we only use indicators linked to the main Circular Economy strategies included in APCE. In accordance with the terminology proposed by Moraga et al. (2019), this first action plan focused on the fourth strategy, "preserve the materials through recycling and downcycling" (Moraga et al., 2019: 454); the first MFCE indicators based on that strategy are therefore chosen. Furthermore, those indicators that approximate the Circular Economy in an indirect way are dismissed, while those that need auxiliary approaches to measure an aspect of CE strategies are built from two or more items of data.

Finally, to prevent the redundancy of information, within Indicator 6 of the MFCE "recycling/recovering for specific waste streams" among the sub-indicators referring to packaging, "Recycling rate of overall packaging" is selected since it includes the following containers: "paper and cardboard", "plastic containers", "wooden containers", "metal containers", and "glass containers".

As shown in Table 3, only 4 indicators meet all the criteria: Recycling rate of municipal waste (RMW), Recycling rate of overall packaging (ROP), Recycling rate of biowaste (RB), and Circular material use rate (CMUR). The 4 indicators selected for the construction of the CECI are described in Table A1 of the Appendix.

Since the selected indicators are measured in differing units, prior to the construction of the CECI, the data is normalised using the Min-Max method (Busu and Busu, 2018; Kasztelan, 2020; OECD, 2008; Silvestri et al., 2020). Min-Max allows a simple and intuitive comparison of the countries in the sample since it provides a positive result between 0 and 1 for easy interpretation. Additionally, it is used widely for the construction of well-known composite indicators such as the Human Development Index (HDI).

Therefore, from expression (1), the data is rescaled from 0 to 1.

$$Y_{ij} = \frac{X_{ij} - Min(X_{ij})}{Max(X_{ij}) - Min(X_{ij})} \quad (1)$$

We subsequently proceed to the *weighting and aggregation* of the normalised indicators. PCA has been used for the weighting: a method created by Pearson (1901) from a geometric perspective, that was later raised algebraically by Hotelling (1933), and widely used to build composite environmental indices (Gatto and Busato, 2020; Jha and Gundimeda, 2019; Jiang et al., 2018; Karman and Pawłowski, 2022; Stanković et al., 2021). This method can be applied when there is a high degree of correlation between the initially chosen indicators, which allows the number of variables to be reduced and one or more composite indices to be proposed, that is principal components, independent of each other and obtained from linear transformations. Principal components explain most of the common variance (OECD, 2008). In addition, in relation to other statistical alternatives, PCA is a simple method, with good mathematical properties and avoids redundant information, thereby allowing comparisons between countries as long as the separate

Table 3
Indicator selection criteria for the construction of the CECI.

INDICATOR	SUB-INDICATOR	SELECTION CRITERIA				
		Data Available	27 EU	Updated to 2020	4th Strategy (Moraga et al., 2019)[1]	Direct measure[2]
1. EU self-sufficiency for raw materials		✓	x	x	✓	x
2. Green public procurement		x	–	–	–	✓
3. Waste generation	3.1. Generation of municipal waste per capita	✓	✓	✓	x	✓
	3.2. Generation of waste excluding major mineral waste …	✓	✓	x	x	✓
4. Food waste		x	–	–	–	✓
5. Recycling rates	5.1. Recycling rate of municipal waste	✓	✓	✓	✓	✓
	5.2. Recycling rate of all waste excluding …	✓	✓	x	✓	✓
6. Recycling/recovering for specific waste streams	6.1. Recycling rate of overall packaging	✓	✓	✓	✓	✓
	6.2. Recycling rate of plastic packaging	✓	✓	✓	✓	✓
	6.3. Recycling rate of wooden packaging	✓	✓	✓	✓	✓
	6.4. Recycling rate of e-waste	✓	✓	x	✓	✓
	6.5. Recycling rate of biowaste	✓	✓	✓	✓	✓
	6.6. Recovery rate of construction and demolition waste	✓	✓	x	✓	✓
7. Contribution of recycled materials to raw material s demand	7.1. End-of-life recycling input rates (EOL-RIR), aluminium (%)	✓	x	x	✓	✓
	7.2. Circular material use rate	✓	✓	✓	✓	✓
8. Trade in recyclable raw materials	8.1. Trade in recyclable raw materials: Imports from non-EU countries	✓	✓	✓	✓	x
	8.2. Trade in recyclable raw materials: Exports to non-EU countries	✓	✓	✓	✓	x
	8.3. Trade in recyclable raw materials: Intra EU trade	✓	✓	✓	✓	x
9. Private investments, jobs, and gross value added	9.1. Gross investment in tangible goods	✓	✓	x	✓	x
	9.2. Employees	✓	✓	x	✓	x
	9.3. Value added at factor cost	✓	✓	x	✓	x
10. Patent related to recycling and secondary raw materials	Number of patents related to recycling and secondary raw materials	✓	✓	x	✓	x

Notes: [1] See Table 1. [2] Direct indicators: those which measure CE strategies in a specific or non-specific way, without the need for auxiliary approaches, are based on a single piece of data that can be obtained from a unique measurement.
Source: Authors' own based on the MFCE (European Commission, 2018) and on Moraga et al. (2019).

indices are calculated using the same variables. However, it should be taken into account that it generates only ordinal composite indicators that lack socio-economic information (Somarriba and Pena, 2009).

Having performed the relevant statistical tests, which show robust results, a single Principal Component is obtained whose explained variance is greater than 69%. This allows us to simplify the information into a single composite index, thereby saving the complexity of multiple indices and avoiding the problem that arises from the aggregation of several Principal Components, since they are orthogonal and uncorrelated (OECD, 2008).

The aggregation of the sub-indicators for the construction of the CECI has been carried out linearly (OECD, 2008) following expression (2).

$$CECI = \sum_{i=1}^{4} w_i I_i \tag{2}$$

where for each of the 4 years and territories considered, I_i are the values of the 4 one-dimensional sub-indicators chosen (i = 1, …,4) and w_i correspond to the weights of each indicator obtained from the PCA component score coefficient matrix, rescaled between 0 and 1.

The results of the statistical tests [Bartlett's sphericity test, Kaiser-Meyer-Olkin (KMO) measurement conditions], which endorse the suitability of the proposed aggregation and weighting methods have been included in the complementary material. The PCA has been carried out using version 27 of the SPSS program.

Once the index has been obtained for each of the 4 years considered, the results have been placed in descending order, thereby allowing a second normalisation to be applied using the ranking technique, which is the simplest normalisation method that remains unaffected by outliers (OECD, 2008). In this way, it is possible to compare the relative position of the countries in the different years of study, which presents the advantage of obtaining intuitive results that are easily transmittable to citizens.

The proposed methodological strategy enables a global and simple index to be obtained that reflects the advances of the EU in Circular Economy in a synthetic and intuitive way based on the material preservation strategy. From the CECI performance, two types of analyses are carried out: a static analysis to determine the countries with the best and worst performance, and a dynamic analysis to assess their evolution.

4. Results and discussion

By applying the methodology described, the CECI is constructed from a single principal component that meets the KMO measurement conditions of sampling suitability and the Bartlett sphericity test, whereby robust results are obtained for both tests. For each of the four years under consideration, the weighting of sub-indicators has been performed through the component score coefficient matrix rescaled to 1 (see Table A2 of the Appendix). The four sub-indicators present very similar weights for the years considered, especially regarding the Recycling Rate of Municipal Waste (RMW).

Table 4 includes the results of the 2020 CECI for the average of the EU, and for its Member States, ordered in ranking and classified into quartiles (Table A4 of the Appendix shows the CECI for 2014, while the remaining tables can be found in the supplementary material). From the CECI of 2020, a first *static analysis* can be carried out of the situation at the end of the APCE. Large differences are found between the Member States especially in the first quartile: the Netherlands (0.876), Belgium (0.782), and Germany (0.739). The worst data corresponds to Romania (0.030), Malta (0.088), and Cyprus (0.179). On the one hand, these results are partially in line with other research studies in terms of the first positions of the ranking, whereby they coincide with studies such as that of García Bernabeu et al. (2020), Giannakitsidou et al. (2020), Kasztelan (2020), Stanković et al. (2021), while on the other hand they coincide regarding their coincidence with the head of the classification (Stanković et al., 2021). They cannot be fully compared, however, because no study has been found with such an up-to-date index (2020).

Table 4
CECI 2020. European union circularity ranking.

1	Netherlands *(NE)*	0.876	15	Lithuania *(LT)*	0.458
2	**Belgium** *(BE)*	0.782	**16**	**Sweden** *(SE)*	0.409
3	**Germany** *(DE)*	0.739	**17**	**Estonia** *(EE)*	0.403
4	**Luxembourg** *(LU)*	0.721	**18**	**Ireland** *(IE)*	0.382
5	**Austria** *(AT)*	0.709	**19**	**Latvia** *(LV)*	0.346
6	**Italy** *(IT)*	0.701	**20**	**Poland** *(PL)*	0.331
7	**Denmark** *(DK)*	0.578	**21**	**Portugal** *(PT)*	0.306
8	**Slovenia** *(SI)*	0.563	**22**	**Bulgaria** *(BG)*	0.299
9	**France** *(FR)*	0.539	**23**	**Hungary** *(HU)*	0.259
10	**United Kingdom** *(UK)*	0.515	**24**	**Croatia** *(HR)*	0.238
11	**Slovakia** *(SK)*	0.514	**25**	**Greece** *(EL)*	0.234
12	**Spain** *(ES)*	0.507	**26**	**Cyprus** *(CY)*	0.179
13	**Finland** *(FI)*	0.502	**27**	**Malta** *(MT)*	0.088
14	**Czechia** *(CZ)*	0.489	**28**	**Romania** *(RO)*	0.030

Source: Authors' own

For the *dynamic analysis*, the results of the CECI 2014, 2018, 2019, and 2020 (Fig. 2) are compared. Although the differences between Member States remain high, they have been reduced globally in the 5 years of validity of APCE (Table A3 of the Appendix shows the decrease in the standard deviation from 0.2136 to 0.2091). However, in the latter years of the period considered, the differences have undergone a slight increase.

On the other hand, Fig. 2 shows progress in the EU and its Member States towards circularity after the implementation of the APCE. Although the average CECI of the EU increased by 17.89% between 2014 and 2020, similar to that of Giannakitsidou et al. (2020), this progress is found to be heterogeneous across the different Member States.

The countries that experienced the greatest improvement in their transition towards circularity between 2014 and 2020 were: Slovakia (whose increase of 163.22% raises it 12 positions); Greece (which improves by 94.58% and rises from position 27 to 25); and Malta (with an increase of 68.60%, raising it from position 19 to 10). In contrast, we find certain decreases: Romania (which, with a decrease of 76.72%, drops by 2 positions); Sweden (down 20.84%, and falls from position 9 to 16); and Denmark (which suffers a decrease of 7.08% and drops by two positions).

Given that one of the objectives of this work involves obtaining intuitive results that facilitate communication to citizens, following other authors (Karman and Pawłowski, 2022; Silvestri et al., 2020; Stanković et al., 2021), we present the results of the CECI in cartographic form (Fig. 3 includes a choropleth map for 2020 while that for 2014 is given in Figure A1 of the Appendix: the rest can be found in the supplementary material).

For the correct interpretation of the results of the CECI, in addition to that of APCE, it is necessary to consider both the initial situation of the Member States and the Circular Economy actions specifically developed for each country in its territory. Thus, the Netherlands provides a reference in Circular Economy and is a pioneer in the application of circular policies (Cramer, 2022), with the goal of being completely circular by 2050. In fact, the Netherlands is currently at the forefront of global circularity, with 24.5% circularity (Wit and Haigh, 2022). Regarding the countries with the worst performance, an influencing factor, according to Momete (2020), is that, in 2016, countries such as Bulgaria, Romania, and Greece were still unprepared to begin their transition to the Circular Economy; this renders it difficult to apply European policies in their territories.

Finally, it should be noted that the results obtained from the CECI analysis agree with those of previous studies that find a positive link between performance in economic circularity and: GDP per capita (Grdic et al., 2020; Marino and Pariso, 2020), socio-economic development measured through the HDI (Stanković et al., 2021), the time spent by the Member States in the European integration process

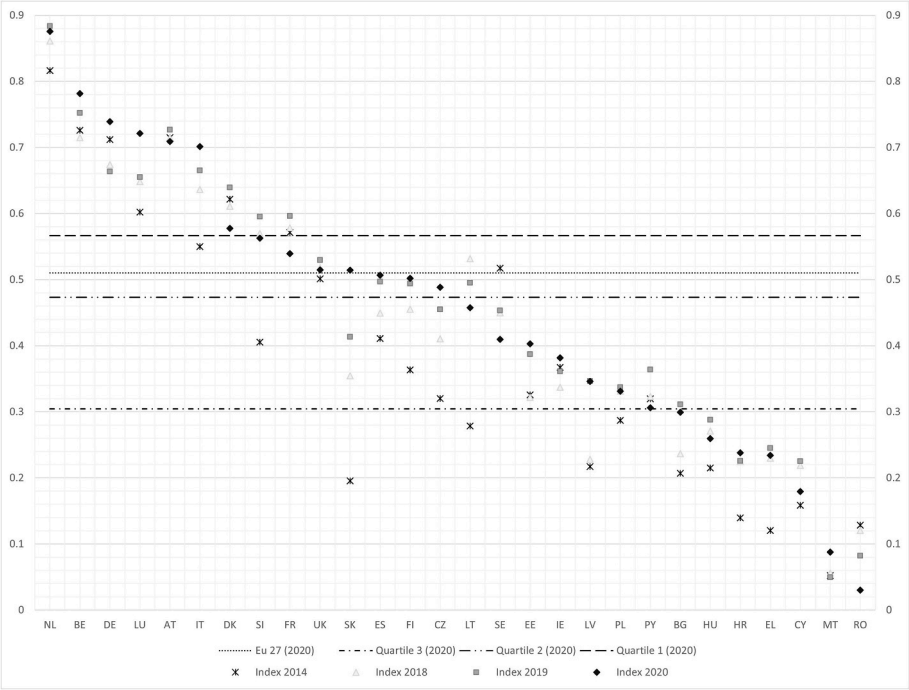

Fig. 2. CECI 2014, 2018, 2019, and 2020: Comparative analysis per member state of the EU.
Source: Authors' own

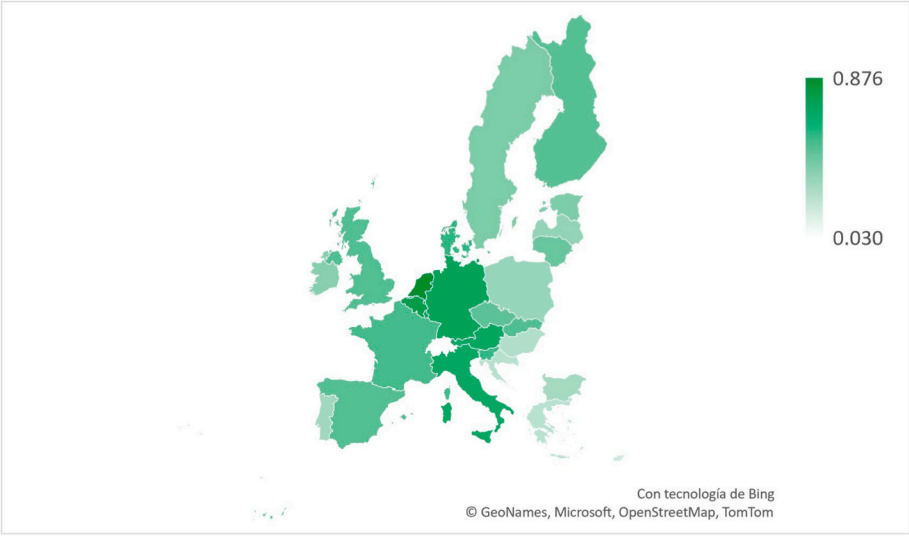

Fig. 3. Circularity Choropleth map. CECI, 2020.
Source: Authors' own

(Domenech and Bahn-Walkowiak, 2019), and its geographical location in the centre of Europe (Silvestri et al., 2020).

5. Conclusions

To assess the effectiveness of any type of policy, it is necessary to have a broad set of instruments that allow the results of the adopted political decisions to be measured and compared with the objectives pursued. In order to quantify the progress in the Circular Economy after the implementation of the EU, first APCE, a Circular Economy composite index, has been built based on recycling and downcycling for the EU Member States in the years 2014, 2018, 2019, and 2020.

To the best of our knowledge, CECI is the first index not only from which the Circular Economy transition derived from the entire program of APCE can be quantified in a global, simple, intuitive, representative way, but it also covers its entire time horizon. For its construction, the direct one-dimensional indicators of the MFCE have been chosen, which are identified with the Circular Economy strategy on which this Plan is based as a priority: "Preserve the materials through recycling and downcycling". It can be considered a *simple and intuitive* index for several reasons. On the one hand, only the most significant sub-indicators have been chosen, thereby preventing repetitions (RMW, ROP, RB, and CMUR). On the other hand, ACP has been used as the aggregation and weighting methodology, and a single principal component is obtained. Furthermore, the results are presented as normalised in a ranking of countries, which simplifies their interpretation and excludes outliers.

Finally, choropleth maps have been built that facilitate communication of the CECI performance in an intuitive and rigorous way. In this way, the CECI is useful for the EU policy-makers as a tool both to monitor progress in the circular transition and to communicate and raise awareness among companies and citizens.

As an average in the EU, not only do the results of the CECI reveal major advances in the Circular Economy transition, but they also show significant differences between its Member States. Although these discrepancies have been reduced overall during the APCE period, in recent years this rapprochement between countries has slowed down. Factors that can explain the disparities between Member States include their individual starting situations and the dissimilar level and form of application of APCE strategies exerted by each country (Domenech and Bahn-Walkowiak, 2019).

Despite these advances, significant challenges are still pending for the completion of circular transition in the EU. On the one hand, encouragement is necessary for the transition to continue, in order to gain homogeneity within the EU; this is especially true in countries with dire initial situations. In this respect, one alternative could involve intensifying the actions of exchange and visibility of good practices carried out in the most advanced territories, which would serve as a model for those that are lagging behind. For example, the creation of the regional centres, such as the Ljubljana Regional Centre for Waste Management (RCERO Ljubljana, Slovenia), which was established for environmentally friendly waste management, and the creation of deposit return systems to repay containers for recycling in countries such as Lithuania and Germany.

It would also be advisable to promote coordinated actions from the EU in order to prevent differences in national policies from hindering convergence in this area. On the other hand, given that APCE has specifically focused on recycling and downcycling (Moraga et al., 2019), the challenge in the coming years involves both extending the actions to encompass the remaining strategies that remain in a less developed stage and intensifying research and action in the field of the Sustainable Circular Economy.

The coming years will present a golden opportunity to take on these challenges since, in addition to the political will (European Green Deal) and the new CEAP, the EU now has the necessary funding. The NextGenerationEU package (European Commission, 2020c), created to alleviate the effects of the Covid pandemic, represents an additional injection into the Multiannual Financial Frameworks (MFF) 2021-27 of €750,000 million. With this injection of capital, which is practically double that of the budget allocation of other MFFs, the EU has prioritised digital and ecological transitions. Thus, at least 30% of these additional funds must be invested in ecological transition.

This research has its limits since it fails to take into account all the strategies contemplated in the MFCE: it is focused solely on recycling and downcycling. Furthermore, all the indicators referring to this strategy have been dismissed due to the lack of data availability from all EU countries for certain indicators, and hence future lines of research can involve the assessment of the remaining strategies and/or the completion of this indicator when data becomes available. As another line of future research, an adaptation of the methodology applied in this work is proposed for the construction of a composite index that enables an assessment of the progress subsequent to the implementation of the CEAP taking as reference the revised MFCE. The MFCE review was carried out on 15 May 2023, and includes a new stage of the EC called Global sustainability and resilience which includes two new indices: 1) Global sustainability from the Circular Economy; and 2) Resilience from the Circular Economy. This improved MFCE would provide an opportunity to build a new and more ambitious composite index and thereby contribute towards achieving environmental policies of greater effectiveness in the EU.

CRediT authorship contribution statement

María Magdalena Martínez Moreno: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Eva M Buitrago Esquinas:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Rocío Yñiguez:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Miguel Puig-Cabrera:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

"Thata are avaliable in \"https://ec.europa.eu/eurostat/web/circular-economy/monitoring-framework\""

Acknowledgements

This research is funded by National Funds provided by FCT- Foundation for Science and Technology through project UIDP/04020/2020 and project 101071300 Sustainable Horizons (HORIZON). The research is also supported by the Research Groups of Research in Applied Economics (SEJ132, SEJ 258. Plan Andaluz de Investigación, Junta de Andalucía, Spain) and Cátedra de Economía de la Energía y del Medio Ambiente sponsored by Red Eléctrica de España at the University of Seville.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.138759.

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