Journal of Environmental Management 373 (2025) 123835

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Assessment of European countries' national circular economy policies

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ARTICLE INFO

Keywords:
Circular economy
European national policies
Data envelopment analysis
Sequential Malmquist index

ABSTRACT

The circular economy (CE) has become key to achieving the environmental objectives set by the European Union (EU). This transformative process requires linear production processes to be abandoned and replaced with environmentally-friendly circular models. In this scenario, the present study uses Data Envelopment Analysis and the Sequential Malmquist Index to achieve a twofold objective: (1) to analyse the effectiveness of the national CE policies applied by 19 EU Member States and (2) to identify the items of circularity that need improvement, in order to support decision-makers in the implementation of appropriate CE policies. The results confirm that the measures adopted have had a positive impact, leading to more efficient circular patterns designed to achieve the desired climate neutrality. Policymakers should focus on resilience and international cooperation, without overlooking environmental sustainability and the need to control excessive resource extraction.

1. Introduction

Climate neutrality requires a universal commitment aimed at achieving the long-desired ecological transition, bringing about a change in production and consumption habits to orient them towards sustainable practices. In this respect, the European Union (EU) aspires to lead this stage of the process and become a global point of reference by establishing the guidelines needed to guarantee real solutions to the planet's climate emergency. The European Green Deal sets out a policy pathway to work towards finding legal tools that help ensure not only that contributions outweigh consumption but also that all countries are fully engaged (European Commission, 2019). This objective will be brought to fruition through the European Climate Law (European Commission, 2021a). The commitment to reduce emissions by at least 55% by 2030 (Fit for 55), 90% by 2040 and 100% by 2050 means all economic sectors must undergo a profound transformation, putting an increasingly high price on pollution (European Commission, 2021b).

This transition requires an environmentally-friendly model, reforming the traditional "extract, produce, use and discard" linear economic system to make it more circular (Schot and Kanger, 2018; Boonman et al., 2023). The ultimate goal of the circular economy (CE) is to extend product lifespans through the reuse, refurbishment, repair and recycling of materials, minimizing the generation of waste (Arijeniwa et al., 2024). The figures speak for themselves: each European generates nearly 180 kg of packaging waste per year, and industry is responsible for 9.10% of greenhouse gas emissions, while waste management accounts for 3.32%. This problem is exacerbated by the trade deficit in raw materials: in 2021, imports exceeded exports by more than 35.5 billion euros (European Parliament, 2023).

The necessary shift towards circularity requires the decoupling of economic growth from resource use, with the CE being introduced at all levels of industry and in people's daily lives. This will make it possible to alleviate the existing pressure on raw materials and tackle biodiversity loss (European Commission, 2020a). Much remains to be done, however. Bianchi and Cordella (2023) estimate that the resource extraction linked to economic growth is four times greater than the savings achieved through different CE initiatives. A huge effort is needed from all the parties involved, fostering innovation and social support for the most vulnerable to achieve full CE implementation (European Commission, 2023). Promoting education and communication helps to raise public awareness and helps ensure the adoption of measures aimed at reducing the demand for natural goods (Cooney et al., 2023).

The CE has sparked great interest in the scientific community, which is attempting to provide evidence to facilitate the spread of this model. For example, authors such as Piscicelli (2023) and Neligán et al. (2023) analyse the role of new digital technologies to maximize the use of

This article is part of a special issue entitled: Regulatory Pathways published in Journal of Environmental Management.

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https://doi.org/10.1016/j.jenvman.2024.123835
Received 13 May 2024; Received in revised form 7 October 2024; Accepted 21 December 2024
Available online 28 December 2024

resources, while minimizing emissions and waste. Others have focused on specific sectors such as construction (Ding et al., 2023), the textile industry (Reike et al., 2023), the food supply chain (Kumar et al., 2023), and some have linked the CE to sustainable business performance (Yin et al., 2023). What they all have in common is the goal of alleviating the arduous task of curbing climate change.

There has also been much debate about the possible connection between the CE and the main macroeconomic variables, growth and employment (Moreno-Mondéjar et al., 2021; Sulich and Soloducho-Pelc, 2022). It has been shown that certain economic policies simultaneously hinder and further the adoption of new green technologies. For instance, Ren and Albrecht (2023) confirm the dual role of environmental taxation, arguing that it has a direct negative effect on the funds that could be allocated to CE innovation, but at the same time may drive businesses to develop activities that achieve resource savings. However, Aguilar-Hernández et al. (2021) confirm the positive impact of fiscal pressure on GDP, employment and emissions reduction, finding that it constrains extraction and represents a source of public revenues that can be targeted at promoting the efficient use of materials. For his part, Camilleri (2020) evaluates the CE plans focused on meeting the goal of climate neutrality set by the European Commission, without neglecting international competitiveness concerns. Bongers and Casas (2022) demonstrate a positive relationship between the circularity of the economy and economic development, the latter realized in terms of output and social welfare.

The literature confirms the positive link between macroeconomic policies and the implementation of CE instruments (Melo et al., 2022; González Forastero, 2023; Murano and Tavares, 2023). Academia has recently made a significant effort to advance the knowledge that can aid decision-makers. For instance, Arranz and Arroyabe (2023) confirm the pivotal role played by institutional policies in promoting CE products. Authors such as Fadeeva and Van Berkel (2021) and Seyyedi et al. (2023) focus on plastic pollution policies, highlighting the need for greater involvement by governments, industry, society and the scientific community in order to improve these policies. In their study of waste paper management, Chen et al. (2023) conclude that local-level fiscal policy measures are crucial to facilitate the implementation of a CE. Similarly, Agovino et al. (2024) highlight the impact of European regulation on waste management in the CE.

The scientific community has evaluated CE strategies in various contexts, including business (Palea et al., 2023; Stucki et al., 2023), water resource management (Koseoglu-Imer et al., 2023), batteries (Barkhausen et al., 2023), and food waste (Landells et al., 2024). These evaluations not only provide insights into the issue, but have also led to the proposal of performance assessment indices (García-Sanchez et al., 2021). At the national level, Shabanpour et al. (2024) estimate the degree of circularity and eco-efficiency in OECD countries. However, there is a notable gap when it comes to assessing the impact of government measures taken to increase resource use efficiency. This research seeks to fill said gap by conducting a study aimed at quantifying the adequacy of the CE strategies adopted, identifying items that need more attention. Thus, this paper has two objectives: (1) to assess the impact of the implementation of national CE policies in EU countries and (2) to identify the items on which authorities should focus to improve the effectiveness of their regulations. Given the EU's leadership and involvement in the fight against climate change, the study focuses on the European countries that have passed national CE policies. Specifically, the analysis includes 19 EU Member States over the period 2010–2022. The results will allow us to answer the following research questions:

Q1. Have national policies resulted in more efficient CE systems? If so, have there been any advances in productivity?

Q2. Is it possible to adopt common strategies for the entire European territory? What should be the focus of future government measures?

The empirical analysis proposed in this paper is carried out using Data Envelopment Analysis (DEA), a non-parametric technique widely used in the literature. In addition, the Sequential Malmquist Index (SMI) is used to evaluate potential improvements in productivity and identify their source. The statistics of the variables that capture the CE initiatives of European countries have been sourced from Eurostat for the period 2010–2022. This research makes a number of novel contributions that may be directly applicable by EU public bodies: (1) it provides a quantitative measure of the impact of the CE policies implemented, informing policymakers of the importance of their efforts and pointing to countries that could serve as benchmarks for successful CE policy implementation; (2) it detects the advances in productivity that occurred during the analysed period and identifies the source of these advances; and (3) it provides information on the key aspects to be reinforced by environmental policymakers in future regulations.

The rest of the paper is structured as follows: in section 2, a literature review is carried out to establish the conceptual framework of the study; in section 3, the research methodology is described; in section 4, the variables used are presented; in section 5, the results of the empirical analysis are analysed and discussed in relation to the prevailing paradigm; and, finally, the conclusions, the contribution of the study and the limitations are summarized in section 6.

2. Literature review: circular economy framework

In the climate demands agreed at the successive meetings of the Conference of the Parties (COP) held annually since 1995, the CE is positioned as one of the most important instruments for halting environmental decline. However, despite the strong commitment of the 197 member countries, the manifestation of the CE in concrete measures is progressing unevenly across countries. For example, while China has focused its action on waste, the EU considers the consumption and design of products to be paramount, with durability, repair and recycling viewed as essential elements (McDowall et al., 2017). For its part, the USA is fostering innovation in nuclear energy as a clean and reliable source to be incorporated into CE initiatives (Hassan et al., 2023). The laws and regulations included sometimes come into conflict with territorial priorities, giving rise to disparate rates of progress, with the pace being especially slow in developing countries (Toker and Görener, 2023).

Those responsible for formulating government regulations analyse the barriers in order to overcome them and achieve the momentum required in this transition. The social and political aspects should be examined in association with technical and environmental factors in an effort to identify specific strategies (Marsh et al., 2022). Metzger et al. (2023) call for the free circulation of knowledge for the sake of the global common good, so that all innovation actors can share their progress. Studies such as that by Siderius and Zink (2023) argue for technical efficiency over market efficiency to ensure that CE policies are not doomed to fail. The new circular models require green production methods that emphasize pollution control and resource management, but they have to overcome innumerable institutional, organizational, social and technological hurdles (Diaz-Lopez et al., 2019).

The collaboration between governments, universities and companies opens up massive opportunities, channelled towards reinforcing the impact of the CE on air and water quality, energy consumption, waste and even land use, encouraging better care of the planet (Yang et al., 2023). Success will depend on the degree of involvement of all stakeholders (government agencies, manufacturing industries, and individual companies) and on an understanding of the challenges faced in the different sectors (Grafström and Aasma, 2021). Najar et al. (2024) confirm the need for this partnership to minimize environmental burdens and achieve a resource-efficient economy. According to Gedam et al. (2021) the lack of know-how, innovation and economic benefits are the main obstacles slowing the progress of the CE.

Change is thus urgently needed in all production systems, compelling companies to innovate in order to offer competitive and environmentally appropriate products (Suchek et al., 2021). Digitalization facilitates cooperation between parties, accelerating the transition to clean, efficient models (Khatami et al., 2023). Tiwari et al. (2024) advise managers to leverage I4.0 technologies to drive circularity in supply chains. However, the degree of implementation of digitalization and the required regulations vary according to the industrial sector and the size of the companies; manufacturing firms show a notably limited use of the type of digital technology capable of supporting sustainable actions (Schöggl et al., 2023). Against this backdrop, academics have shown great interest in analysing the policies and laws that seek to strengthen the development of the CE (Table 1).

The success of the transition revolves around official guidelines, business models and public awareness (Wasserbaur et al., 2022). Studies by the scientific community have provided insights for public and private leaders to ease the journey on this path of no return. The situation the planet is facing demands radical change at all levels in order to try to halt the environmental deterioration, the consequences of which are becoming increasingly evident. There is thus a universal duty to alter production and consumption models to make them more environmentally friendly. In this context, CE policy seeks to reduce dependence on finite resources to avoid compromising the future of upcoming generations (Terra dos Santos et al., 2023). However, what we see in reality is varying degrees of involvement, with delays in fulfilling the objectives set out at the COP meetings. Accordingly, there is a critical need for an assessment of the national policies adopted by countries in one of the geopolitical entities most committed to climate change, the EU.

3. Research methodology

There is an evident need to define a circular model, given issues such as the finite nature of raw materials, the increasing demand for them, foreign dependence, and environmental deterioration. In order to conduct the proposed study, we have established a workflow diagram to facilitate the analysis of the different stages of the CE and their applications (Fig. 1).

The model has been designed to evaluate the performance of each country in the stages defined, as well as the possible impact of national CE policies. The ultimate goal is to ensure global sustainability, resilience, and international engagement through trade. The statistical information for all the variables has been sourced from Eurostat and covers the 13-year period from 2010 to 2022, the year with the latest available data.

3.1. Methods: data envelopment analysis and the Sequential Malmquist Index

DEA is a non-parametric linear programming technique for measuring the relative efficiency of a set of decision-making units (DMUs), defined by multiple inputs and outputs. The original method is attributed to Charnes et al. (1978), developed as a direct extension of the work by Farrell (1957). It consists of constructing, based on a production function, an efficient frontier made up of the DMUs that have managed to maximize their outputs with the available resources (output orientation, oo), or vice versa, minimize the resources used to obtain a given amount of output (input orientation, oi). The degree of inefficiency of the rest of the DMUs is measured by their distance to the defined frontier. The approach was initially linear, assuming constant returns to scale; that is, proportional changes in inputs and outputs. To address this limitation, Bankers et al. (1984) developed DEA under variable returns to scale (VRS), making it more flexible. This method has been widely used in sustainability studies to examine issues such as water supply savings (García-Mollá et al., 2021), innovation (Puertas et al., 2022), social start-ups (Sanchez-Robles et al., 2023) and even water security policies (Castro-Pardo et al., 2022). DEA was chosen for this analysis because it enables an assessment of the efficiency of the different stages through which the CE passes, providing a quantitative measure of the

Table 1
CE-promoting policies and laws.

Author	Data	Policies and laws
Hartley et al. (2020)	47 experts from the EU's public and private sectors.	(1) Adoption of circular design standards and norms at EU level, (2) expansion of green public procurement, (3) alterations to taxes on CE-based products, (4) liberalization of waste trading, (5) support for circular trading platforms, (6) creation of eco-industrial parks, (7) CE marketing and promotion campaigns, (8) more statistical information on global material flows
Fan and Fang (2020)	31 Chinese regions	(1) Regulation on the use of regional resources, (2) codes of conduct for cooperation in industrial parks, (3) laws on regional environmental standards and evaluation systems, (4) motivation mechanisms through tax policies for companies and researchers, (4) preferential forms of financing, (5) support for dissemination through the media.
Friant et al. (2021)	EU	(1) Measures aimed at generating employment, (2) investments in the social and solidarity economy, (3) restrictions on the export of waste outside the EU, (4) promotion of social cooperatives dedicated to circularity.
Cramer (2022)	Representatives from 16 countries	(1) Long-term supranational policies, (2) mobilization of social and financial support, (3) legislation aimed at the different stages of the life cycle of materials (4) extended producer responsibility.
Giorgi et al. (2022)	5 European countries	(1) Expansion of the legislative framework to promote reuse strategies, encouraging the creation of stakeholder networks, (2) development of harmonized waste management guidelines, (3) support for innovative action.
Munaro and Taveres (2023)	47 articles	(1) Flexible governance policies translated into regulations and taxation, (2) integrated waste and information management system.
Pinyol Aberich et al. (2023)	EU	(1) Alignment of European policies with a circular modernist future, (2) presenting alternative visions of the CE for public debate.
Chioatto and Sospiro (2023)	EU	(1) Price incentives, (2) intervention in consumer electronics, (3) special taxes on waste, landfill and incineration, (4) license fees for recycling, (5) mandatory waste treatment.
Friant et al. (2023)	3 European cities	(1) Promotion of socio-cultural transformation, (2) establishment of participatory mechanisms for the development and enforcement of CE policies, (3) implementation of post-growth urban planning approaches.
Imran et al. (2024)	EU	(1) Promotion of waste management through the adoption of green technologies, (2) improvements to environmental taxation policies, (3) acceleration of the transition to renewable energy.

Source: Own elaboration.

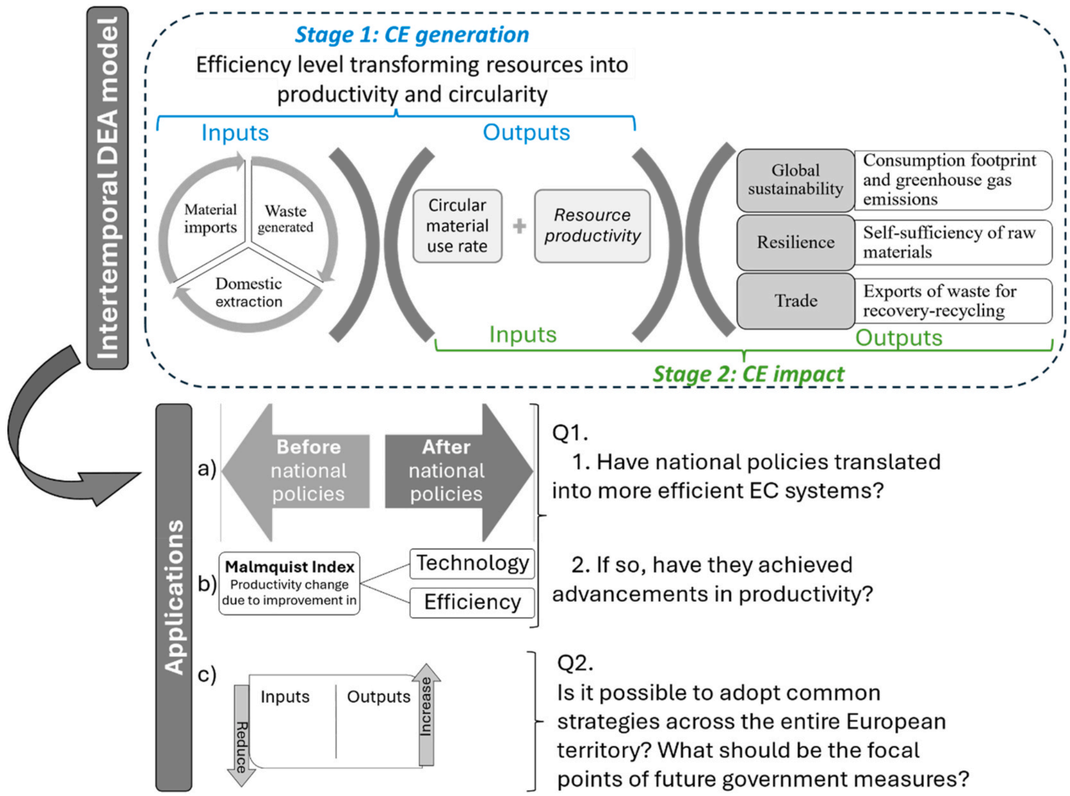

Fig. 1. Methodological framework for addressing the research questions.
Source: Own elaboration.

impact of the public policies adopted. It is a well-established technique recommended for use in scenarios where several stages are under evaluation, offering an unbiased estimate of efficiency (Gennitsaris et al., 2023; Banjerdpaiboon and Limleamthong, 2023), and facilitating the comparative and objective measurement of the efficiency a set of DMUs defined by multiple inputs and outputs (Saeed et al., 2023). The aforementioned studies indicate the robustness of this method given the sample size chosen, the intertemporal nature of the analysis and the consistency of the DMUs.

Given the nature of the issues addressed in this research, we use DEA with oo and VRS, seeking to maximize the outputs with the available resources and allowing the variables that define the model to vary freely. In addition, we adopt an intertemporal approach, enabling comparisons between the different levels of efficiency (Cruz-Cázares et al., 2013; Bresciani et al., 2021). A cross-sectional estimation would only allow an analysis of the annual efficiency of the DMUs. At the same time, the intertemporal DEA provides an overall view of the period analysed, thus preventing distortions in the results caused by specific events and helping to ensure the robustness of the results obtained (Mittal et al., 2005). DEA evaluates the DMUs by detecting the similarities between all the units in the sample; therefore, a single efficient frontier must be constructed that covers all the years under study, rather than annual frontiers, which would preclude comparisons. The efficient DMUs are those with a score of 1, while for inefficient DMUs the amount over 1 indicates the level of inefficiency of the DMU in question. The second research question can be answered by carrying out an individual analysis of all the variables that define the proposed model, comparing their target with the original value.

The Malmquist Index, originally proposed by Caves et al. (1982) and further developed by Färe et al. (1998), identifies the change in productivity and its source, that is, whether it is due to technological advances (Tc) and/or improvements in efficiency (Ec). It is calculated by measuring the distance from the technological frontier of each DMU in two consecutive time periods (t, t+1). Specifically, the SMI has been used, which accounts for the accumulation of knowledge over time. This precludes the need to consider technology loss, which would be difficult to explain in a sector that is constantly introducing new tools (Tulkens and Vanden Eeckaut, 1995). SMI registers values greater than, equal to or less than 1: SMI >1 reflects increases in productivity (1-SMI), SMI $= 1$ when it has remained stable, and SMI <1 evidences a decline in productivity (SMI-1). Both models were estimated using the deaR statistical package installed in Rstudio (Coll-Serrano et al., 2018).

A two-stage model has been formulated to provide additional information and avoid the "black box" treatment of DMUs, shedding light on the intermediate steps taken to reach the desired outputs (Omrani et al., 2022). The initial inputs are thus used to obtain the outputs of the intermediate stage, which in turn will be used to generate the end product (Tavana et al., 2018). The structure proposed in Fig. 1 appropriately captures the stages of the CE. Without losing sight of the ultimate objective of ensuring the health of the environment, self-sufficiency is also evaluated, as well as the degree of international collaboration.

4. Database analysis

The EU has demonstrated a strong commitment to tackling climate change since 2015, passing different action plans aimed at creating a solid and coherent framework to combat the excessive consumption of raw materials, and improving waste management from the earliest stages of product design (European Commission, 2015, 2020b). However, given the complexity involved in developing CE policies, there has been a lag in their translation into institutional regulations, reflecting the degree of engagement of the different governments. This time gap marks the disparities in the progress made by each country. Fig. 2 shows the year of initial implementation for the 20 Member States that have adopted national CE policies and the year they were passed (Geerken

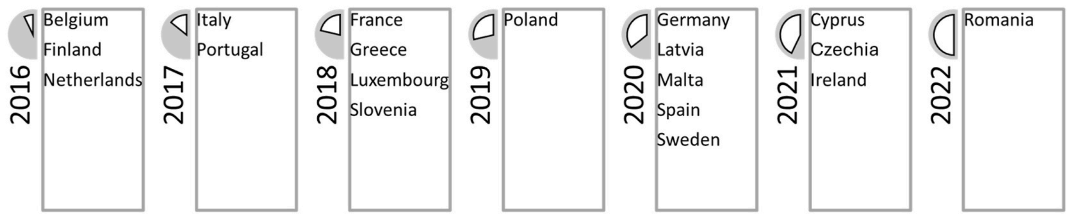

Fig. 2. Year of initial implementation for national CE policies adopted by the EU Member States.
Source: Own elaboration.

et al., 2022).

The impact of CE policies has been assessed by comparing efficiency gains before and after the adoption of national policies. Hence, Romania has been removed from the sample due to the lack of statistical information after 2022, preventing the assessment of the effect of its regulations. The variables used have been selected to represent the different stages of the CE (based on the Eurostat Sankey diagram of material flows), from the first stage, which covers extraction, waste management and raw material imports, to their overall impacts on the country (Table 2). They are expressed as per capita measurements to ensure the results are not affected by the size of the countries.

The variables of Stage 1 allow us to calculate countries' level of efficiency in transforming their resources into productivity and circularity, while in Stage 2 we assess whether these practices have managed to reduce foreign dependence, helped to achieve climate neutrality and supported the trade in recyclable raw materials. The descriptive statistics corroborate the disparities among the analysed countries (Appendix Table 1A).

5. Results and discussion

Despite the EU's strong commitment to tackling climate change, the Member States have taken varying lengths of time to adapt their internal regulations to EU requirements, with some countries yet to regulate. The first aim of the analysis is to determine the level of effectiveness of their CE policies. Efficiency is calculated for the entire period (2010–2022) and then individualized for each country, determining the average efficiency before and after the implementation of environmental regulations. This research question allows for expanding the theoretical framework presented in the introduction, particularly regarding the transition from linear to circular production models (Schot and Kanger, 2018; Boonman et al., 2023). The efficiency improvements observed in the national CE policies demonstrate the practical application of these concepts.

Table 3 shows the results of the intertemporal DEA. Specifically, the columns present the following information: column (1) indicates the year of initial implementation of the CE policies in each country. (2) the year the national policies were adopted (t); (3), (4) and (5) the mean efficiency levels achieved in stages 1, 2, and overall CE, respectively, during the period 2010 - t; (6), (7) and (8) the corresponding mean values from t+1 to 2022; and, finally, (9) the impact of government regulations, calculated as the difference between (8) and (5). The amount over 1 indicates the degree of inefficiency. Thus, it is worth noting that in Belgium, before the CE guidelines, the system registered an inefficiency of 30.2%, with 16% corresponding to the first stage and 12.2% to the second. After implementing regulations in 2016, inefficiency fell to 6.2%, demonstrating that national CE policies have improved circularity by 24 percentage points.

A positive impact can be seen almost across the board, with the performance of Germany and Ireland particularly standing out. These are countries that, despite having lagged behind in the introduction of specific CE regulations, show advances of over 31% and 29%, respectively. On average, the effects in the EU have been higher in the first stage (before the implementation of national policies the average inefficiency is 18.3% and it drops to 9.5% after implementation) than in the second stage, where the inefficiency reaches 1.4% (Table 3). Based on these results, we can confirm that the implementation of national CE policies has resulted in more efficient systems (13.3%), helping to

Table 2
Variables of circular economy stages.

Stage 1. CE generation				
	DMUs	Definition	Measure unit	Authors
Input	Domestic extraction	Natural resources extracted for input into the production process	Tonnes per capita	Shabanpour et al. (2021)
Input	Waste generated	Waste generated by households, business, offices, public institutions	Kilograms per capita	Shabanpour et al. (2024)
Input	Material import	Natural resources purchased from other countries	Tonnes per capita	Liu et al. (2019)
Output	Circular material use rate	The material recycled and fed back into the economy as a share of overall material use	Percentage	Giannakitsidou et al. (2020)
Output	Resource productivity	Gross domestic product divided by domestic material consumption	Euro per kilogram	Wang et al. (2021)
Stage 2. CE impact				
Input	Circular material use rate	The material recycled and fed back into the economy as a share of overall material use	Percentage	Giannakitsidou et al. (2020)
Input	Resource productivity	Gross domestic product divided by domestic material consumption	Euro per kilogram	Wang et al. (2021)
Output undesirable	Consumption footprint	The environmental impacts of consumption: food, mobility, housing, appliances and household goods	Weighted score per inhabitant	Shabanpour et al. (2024)
Output undesirable	Greenhouse gas emissions	Greenhouse gas emissions from all production activities	Kilograms per capita	Shabanpour et al. (2021)
Output	Material self-sufficiency	The degree to which the country does not have to rely on other countries for the supply of several raw materials.	Percentage	Eurostat (2024)
Output	Waste export	Trade of waste between countries for further treatment	Tonnes per capita	Liu et al. (2019)

Source: Own elaboration.

Table 3
Impact of national CE policies.

Country	National policies[a]	EFF before national policies			EFF after national policies			National policies effects
		EFF Stage 1 [2010-t]	EFF Stage 2 [2010-t]	EFF CE [2010-t]	EFF_Stage 1 [(t+1)-2022]	EFF_Stage 2 [(t+1)-2022]	EFF CE [(t+1)-2022]	
Belgium	2016	1.160	1.122	**1.302**	1.007	1.054	**1.062**	**24.0%**
Cyprus	2021	1.321	1.124	**1.484**	1.224	1.127	**1.379**	**10.5%**
Czechia	2021	1.119	1.033	**1.155**	1.000	1.057	**1.057**	**9.8%**
Denmark	2018	1.298	1.114	**1.445**	1.174	1.131	**1.327**	**11.8%**
Finland	2016	1.277	1.054	**1.345**	1.266	1.019	**1.290**	**5.5%**
France	2018	1.180	1.081	**1.276**	1.127	1.033	**1.164**	**11.2%**
Germany	2020	1.264	1.235	**1.560**	1.077	1.153	**1.241**	**31.9%**
Greece	2018	1.203	1.012	**1.218**	1.138	1.021	**1.162**	**5.6%**
Ireland	2021	1.287	1.167	**1.502**	1.073	1.128	**1.210**	**29.2%**
Italy	2017	1.154	1.126	**1.299**	1.082	1.123	**1.216**	**8.4%**
Latvia	2020	1.182	1.016	**1.200**	1.060	1.000	**1.060**	**14.0%**
Luxembourg	2018	1.101	1.303	**1.435**	1.014	1.477	**1.498**	**-**
Malta	2020	1.081	1.113	**1.203**	1.000	1.002	**1.002**	**20.2%**
Netherlands	2016	1.015	1.104	**1.120**	1.009	1.081	**1.091**	**2.9%**
Poland	2019	1.040	1.012	**1.053**	1.072	1.024	**1.097**	**-**
Portugal	2017	1.280	1.031	**1.319**	1.177	1.029	**1.211**	**10.8%**
Slovenia	2018	1.170	1.017	**1.191**	1.119	1.014	**1.134**	**5.6%**
Spain	2020	1.111	1.051	**1.167**	1.055	1.027	**1.083**	**8.4%**
Sweden	2020	1.238	1.047	**1.296**	1.134	1.000	**1.134**	**16.2%**
Mean		1.183	1.093	**1.293**	1.095	1.079	**1.180**	**13.3%**

[a] Year of initial implementation of the CE policies.
Source: Own elaboration.

optimize circularity rates (Stage 1), and, to a lesser extent, having a notable positive impact on the health of the climate, as well as the level of self-sufficiency and international cooperation (Stage 2). The results align with institutional theory, reinforcing the idea that comprehensive CE policies lead to significant gains in resource efficiency and sustainability. The improvements in productivity, particularly in countries with strong regulatory frameworks, validate the theoretical predictions made by Schot and Kanger (2018).

The observed improvements in resource productivity and material self-sufficiency across Member States validate the theoretical predictions that strong regulatory frameworks can drive circularity (Arranz and Arroyabe, 2023). These findings further support the idea that the introduction of CE policies leads to both technological advancements and behavioural shifts, as described by Friant et al. (2021).

Although all the regulations have been implemented under the common cause of achieving climate neutrality, the tactics used differ by country. The German CE strategy included in the Resource Efficiency Programme-ProgRess III approved in 2020 is governed by the following guiding principles: (1) associating ecological needs with economic opportunities, innovation and social responsibility, (2) ensuring national resource policy is guided by global responsibility, (3) reducing dependence on raw materials and promoting recycling, (4) supporting quality growth by reinforcing the long-term sustainable use of resources (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2020). In Ireland, on the other hand, the approach adopted combines the elimination of fossil fuels and the introduction of circularity in manufacturing processes through measures aimed at sustainable production and consumption. Its regulations are focused on conserving resources and raising awareness about the importance of the CE among households, companies and individuals. The government has backed greater investment in all regions, actively working to eliminate the economic, regulatory and social barriers to this transition (Government of Ireland, 2021).

The Netherlands, whose programme was approved in 2016, is more oriented towards the design of circular products, promoting the use of renewable raw materials and reducing dependence (Ministry of Infrastructure and Water Management, 2016). For its part, France has focused on waste collection methods, paying particular attention to plastic packaging and biodegradable municipal waste. Citizens are being asked to play a more active role in sorting waste and offered the necessary tools to do so. The government supports these goals through price incentives for waste management, a general tax on polluting activities and, ultimately, an efficient regulatory framework. These initiatives have resulted in a gradual rise in recycling rates, and reduction in biowaste (Ministère de la Transition Écologique et Solidaire, 2018). Table 3 shows a marked improvement in French efficiency (11.2%), while this figure is lower in the Netherlands (2.9%).

Denmark has promoted the transition through financial support for the recycling of materials and environmental innovation, indicating a need for more government incentives to encourage repair and social transactions (Danish Government, 2018). In Portugal, it has been the public sector that has shown strong involvement in the circular agenda, without the backing of the private sector (República Portuguesa, 2017). Conversely, in Spain, the general public, the productive sectors and the authorities are jointly committed to calling for efforts to reduce the use of raw materials and waste generation, as well as for decarbonization through the adaptation of infrastructure and local consumption (Ministry for Ecological Transition and the Demographic Challenge, 2020). In short, it can be concluded that the specific characteristics of each country determine the strategies implemented, and sometimes their outcomes. Their success in terms of efficiency ranges between 31.9% in Germany and 2.9% in the Netherlands.

To strengthen CE policies, decision-makers should introduce more stringent regulations on resource extraction and enforce mandatory recycling and reuse practices. Fiscal incentives for circular production models could also accelerate the adoption of sustainable business practices, as observed in leading EU nations.

Secondly, we have calculated the changes in productivity that have occurred after the implementation of national policies. Table 4 shows a slight rise of 2.3% in the overall CE (SMI, column 9), where 4.3% (SMI, column 3) corresponds to the first stage, with a slight drop in the second (SMI, column 6). It can also be seen that these changes are due exclusively to technological progress, which achieves a rise of 5.8% in the first stage (Tc, column 4) and 2.5% in the second (Tc, column 7), with the latter increase almost entirely attributable to Ireland (36.8%), and to a lesser extent Finland (8.2%) and Luxembourg (2.5%). However, there has not been a visible increase in efficiency in any of the analysed stages (Ec, column 5 and 8), a fact that confirms the need to make better use of resources in order to improve circularity outcomes by enhancing productivity growth. These results are evidence of the modern approach

Table 4
Productivity growth after the approval of the national CE policies.

Country	National policies t[a]	Stage 1 SMI [(t+1)-2022]	Stage 1 Tc [(t+1)-2022]	Stage 1 Ec [(t+1)-2022]	Stage 2 SMI [(t+1)-2022]	Stage 2 Tc [(t+1)-2022]	Stage 2 Ec [(t+1)-2022]	CE SMI [(t+1)-2022]	CE Tc [(t+1)-2022]	CE Ec [(t+1)-2022]
Belgium	2016	1.024	1.024	1.000	0.977	1.000	0.977	1.001	1.024	0.977
Cyprus	2021	1.075	1.120	0.960	0.877	1.000	0.877	0.943	1.120	0.842
Czechia	2021	1.114	1.114	1.000	0.907	1.000	0.907	1.011	1.114	0.907
Denmark	2018	1.035	1.053	0.984	1.000	1.000	1.000	1.035	1.053	0.984
Finland	2016	1.023	1.053	0.972	1.106	1.082	1.020	1.131	1.139	0.993
France	2018	1.019	1.034	0.986	0.991	1.000	0.992	1.010	1.034	0.977
Germany	2020	1.044	1.060	0.985	0.956	1.000	0.957	0.998	1.060	0.942
Greece	2018	1.022	1.046	0.978	0.977	1.000	0.976	0.999	1.046	0.955
Ireland	2021	1.071	1.073	0.998	1.110	1.368	0.811	1.188	1.468	0.810
Italy	2017	1.012	1.032	0.981	1.009	1.000	1.009	1.021	1.032	0.990
Latvia	2020	1.098	1.099	0.999	0.989	1.000	0.988	1.085	1.099	0.987
Luxembourg	2018	1.041	1.041	1.000	1.101	1.025	1.034	1.147	1.067	1.075
Malta	2020	1.030	1.037	0.994	0.829	1.000	0.829	0.854	1.037	0.824
Netherlands	2016	1.044	1.044	1.000	0.973	1.000	0.974	1.016	1.044	0.973
Poland	2019	1.024	1.045	0.980	0.985	1.000	0.985	1.009	1.045	0.965
Portugal	2017	1.026	1.056	0.972	0.993	1.000	0.992	1.019	1.056	0.965
Slovenia	2018	1.031	1.050	0.982	0.979	1.000	0.979	1.009	1.050	0.961
Spain	2020	1.036	1.053	0.984	0.899	1.000	0.902	0.932	1.053	0.885
Sweden	2020	1.038	1.062	0.978	0.982	1.000	0.982	1.020	1.062	0.961
Mean		**1.043**	**1.058**	**0.986**	**0.981**	**1.025**	**0.957**	**1.023**	**1.084**	**0.946**

[a] Year of initial implementation of the CE policies.
Source: Own elaboration.

followed by European CE policies based on technological innovations and the mobilization of firms and customers (Alberich et al., 2023). However, this technology-based approach to circularity has been heavily criticized by academia as incapable of decoupling economic growth from resource use, thus violating the EU's environmental ambitions (Friant et al., 2021; Hickel and Kallis, 2019).

According to Hailemariam and Erdiaw-Kwasie (2023), governments should lead by example, encouraging companies to adopt practices that reduce emissions. This requires solid regulatory frameworks, as well as an educational programme with strong environmental values, without skimping on funding for grants, subsidies, or tax credits to achieve climate neutrality. In this regard, Ul-Durar et al. (2023) show evidence of the connection between environmental innovation and the CE, and suggest that those responsible for sustainability policies should encourage organizational learning to guide companies towards circular practices. Jesus and Jugend (2023) argue that open innovation may be the appropriate instrument for achieving the CE goals, requiring collaboration between stakeholders to ensure their objectives are aligned. However, it should be used in combination with public incentives to provide companies with the necessary financing to introduce CE practices into their production processes (Gutberlet et al., 2023).

By way of example, environmental proactivity in Germany is based on reuse and the promotion of durable products, with repair encouraged through warranty programmes supported by specific CE policies (Erum et al., 2024). Digitally-focused German manufacturing companies have been strongly pushing the implementation of circular business models (Neligan et al., 2023).

In contrast to the figures shown in Tables 3 and 4, the study by Chioatto and Sospiro (2023) reports evidence of a slight positive convergence among European countries in sustainable waste management, but a large divergence in terms of the return to manufacture of secondary raw materials. In addition, the authors note the need to focus efforts on the design of environmentally friendly products, with more financial assistance provided to industries to solve existing technological barriers. According to Marino and Parisino (2020), narrowing the gap between the countries analysed requires strong economic structures, greater efforts by governments, and an entrepreneurial culture supported by greater public awareness.

In terms of managerial decision-making, the findings suggest that businesses should align their operational strategies with CE principles, particularly in adopting resource-efficient technologies. The improvement in productivity and reduction in waste generation provide a roadmap for managers to enhance sustainability while maintaining economic growth (Alberich et al., 2023). Thus, this study offers practical guidance for decision-makers to leverage CE policies for competitive advantage in the evolving regulatory landscape.

Having analysed the impact of EU Member States' CE policies and confirmed that they have resulted in slight improvements in productivity, it is worth trying to shed some light on the aspects requiring more work. Table 5 shows how much the variables that define the CE model would have to change to achieve the maximum level of efficiency; specifically, to reduce inputs and increase outputs. In the latter case, since there are two "undesirable" items (*greenhouse gas emissions* and *consumption footprint*), the percentage decrease is shown. Information on intermediate variables is not included, as their dual status as input/output variables could lead to confusion.

The results reveal that government efforts should chiefly centre on boosting outputs, without overlooking the need to reduce extractions (12.2%) and waste generation (3.6%), both issues addressed in all European CE regulations. The increase in natural resource self-sufficiency does not entail domestic extraction but rather a reduction in the demands of the productive sectors (48.1%). In addition, countries should promote waste trade focused on recycling and reuse (44.9%), as this would reduce domestic extraction. Finally, these finding emphasize a significant social implication: more stringent regulations are needed to reinforce the goal of zero emissions and consumption without environmental impacts (13.3% and 11.1%, respectively). Again, these last items show more modest values due to the strict policies currently in force.

However, government measures must be adapted to meet the needs of each country. For example, Finland has to place greater restrictions on *domestic extraction* (53.1%) and *waste generation* (19.4%), while other countries such as Italy should focus their efforts on improving *material self-sufficiency* (41.2%) and *waste export* (236.8%), as well as reducing *greenhouse gas emissions* (26.3%) and the *consumption footprint* (14.1%).

Recent research makes the case that a change in the degree of dependence fosters self-sufficiency and a reduction in materials, constraining global warming by reducing emissions (Palle Paul Mejame et al., 2023). Technological advances would be a boost to the efficiency of recycling systems and material self-sufficiency, requiring more ambitious public and private strategies that address the shifting

Table 5
Orientation to national CE policies.

Country	Inputs (Reduce)			Output (Increase)			
	Domestic extraction	Waste generated	Material imports	Material self-sufficiency	Greenhouse gas emissions	Consumption footprint	Waste export
Belgium	0.5%	3.7%	0.0%	107.6%	−6.6%	−18.1%	5.4%
Cyprus	6.1%	10.5%	0.0%	12.7%	−15.1%	−16.7%	12.7%
Czechia	0.0%	0.0%	0.0%	5.7%	−9.2%	−10.6%	5.7%
Denmark	39.5%	24.4%	0.0%	13.1%	−40.7%	−25.7%	13.0%
Finland	53.1%	19.4%	0.0%	1.9%	−5.9%	−9.7%	2.6%
France	2.1%	0.1%	0.0%	3.4%	−8.0%	−5.0%	20.2%
Germany	13.2%	6.9%	0.0%	15.3%	−19.1%	−20.5%	58.0%
Greece	0.0%	0.0%	0.0%	5.4%	−2.5%	−4.1%	2.0%
Ireland	67.9%	0.0%	0.0%	12.8%	−42.3%	−15.2%	12.8%
Italy	0.0%	0.0%	0.0%	41.2%	−26.3%	−14.1%	236.8%
Latvia	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Luxembourg	0.0%	2.8%	0.0%	524.3%	−48.9%	−37.9%	48.0%
Malta	0.0%	0.0%	0.0%	7.5%	−0.6%	−1.4%	0.2%
Netherlands	0.0%	0.1%	0.0%	136.1%	−6.0%	−14.2%	8.0%
Poland	1.0%	0.0%	0.0%	2.4%	−6.0%	−5.0%	2.4%
Portugal	0.0%	0.0%	0.0%	2.8%	−6.2%	−6.9%	61.4%
Slovenia	0.0%	0.0%	0.0%	2.1%	−2.3%	−2.7%	1.8%
Spain	0.0%	0.0%	0.0%	18.8%	−6.6%	−4.1%	362.4%
Sweden	47.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Mean	**12.2%**	**3.6%**	**0.0%**	**48.1%**	**−13.3%**	**−11.1%**	**44.9%**

Source: Own elaboration.

challenges of the entire supply chain (Baars et al., 2021). According to Rossi and Morone (2023), the authorities have to consider the volume and quality of consumption, seeking to extend the value of resources throughout their life cycle, and monitor the use made of waste in destination countries. The final disposal of waste is sometimes done under environmentally unsafe conditions. Protocols for detecting hazardous substances in recyclable materials must be established to ensure harmless circular cycles (Ahkola et al., 2024).

Therefore, academia advises focusing on the most harmful variables, represented in this study by *material self-sufficiency* and *waste export*. Improvements in these items would bolster Europe's resilience in the face of unforeseen events such as COVID-19 or the war in Ukraine (Lavtizar et al., 2021; Higgott and Reich, 2022).

6. Conclusions

The planet is in a state of emergency: the reality of climate change requires the world's population to modify its consumption and production habits to halt environmental degradation. The CE has been designed as a key instrument to reduce the extraction of raw materials and achieve climate neutrality, by extending the useful life of products. Nevertheless, its implementation requires commitments and efforts that sometimes run counter to private and public goals in a country. The EU is leading the charge in this battle, obliging its Member States to pass ever more stringent laws on recycling, packaging and repair, and the promotion of sustainable products.

This study analyses the impact of the CE regulations applied in the different countries to detect disparities and intensify the necessary measures. It addresses a research gap by quantifying the adequacy of the CE strategies adopted by 19 EU Member States. By evaluating the effectiveness of these policies, the study identifies areas requiring greater attention and improvement, particularly in terms of resource efficiency and the adoption of innovative technologies. The results reveal that, although the approved guidelines have been well received, there remains much to be done. The different rates of implementation are a clear reflection of the countries' degree of engagement, with individual goals sometimes running counter to the global objectives of the European Commission. For example, Germany has improved the efficiency of its circular model by 31.9%; however, it has to strengthen its regulations to alleviate its *domestic extraction* (13.2%), *waste management* (6.9%), *material self-sufficiency* (15.3%), *greenhouse gas emissions* (19.1%), *consumption footprint* (20.5%) and *waste trade* (58%).

6.1. Policy implications and limitations of the study

The European Commission has set a very high bar for all its members, demanding new ways of producing that often translate into major losses for business owners. Reaching the targets requires substantial financial aid together with stricter regulations on foreign trade, preventing a loss of competitiveness against extra-EU products.

Decision-makers should reinforce CE measures with fiscal incentives for circular production process models. Mandatory recycling, reuse, and the implementation of regulations on the durability of products would make it possible to extend the life of products, thereby leading to improvements in key issues such as GHG emissions, the consumption footprint, and the excessive extraction of natural resources. This transition towards circularity is not a choice but a necessity—one that requires radical change at all levels, with regulations linking economic growth to respect for the environment. It calls for a major revolution, where ambitious European environmental targets are backed up by strictly enforced rules.

Research based on statistical data entails limitations related to the availability of information. Specifically, the study carried out could be reinforced if data were available for 2023, as well as greater detail on the incentives and/or taxes imposed by the different governments. Future research should also analyse the impact of resilience on the progress of CE, and this analysis will be based on statistical information provided by Eurostat, providing valuable insights into the future of CE.

CRediT authorship contribution statement

V. Sanz-Torró: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **C. Calafat-Marzal:** Writing – original draft, Investigation, Conceptualization. **J.M. Guaita-Martinez:** Investigation, Conceptualization. **V. Vega:** Writing – review & editing, Supervision, Project administration, Conceptualization.

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.

Acknowledgement

Funding for open access charge: CRUE-Universitat Politècnica de València.

Appendix

Table 1A
Descriptive statistics.

	Domestic extraction	Waste generated	Material import	Circular material use rate	Resource productivity	Material self-sufficiency	Greenhouse gas emissions	Consumption footprint	Waste export
Mean	13.86	533.67	2.09	9.63	2.14	57.69	8,266.29	1.06	0.38
SD	8.64	126.32	1.04	6.82	1.09	20.04	3,034.54	0.18	0.31
Min	3.28	272.00	0.50	0.60	0.48	8.10	3620.34	0.68	0.06
Max	45.99	862.00	4.65	29.00	5.44	84.70	16767.33	1.45	1.28
N°obs.	247	247	247	247	247	247	247	247	247

Data availability

Data will be made available on request.

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