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Closing the loop? Assessing efficiency in advancing circular economy transitions in the EU-27 countries

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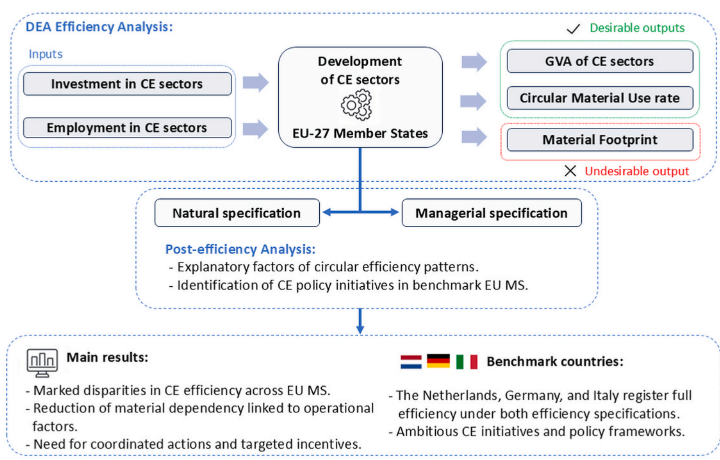
HIGHLIGHTS

- EU countries differ significantly in advancing their CE transition.
- Most countries expand the CE sector without reducing their material footprint.
- GDP per capita and resource productivity significantly affect CE efficiencies.
- Managerial efficiency links also to waste generation (↓) and recycling rates (↑).
- Technological advancements in the CE sector are more evident in Eastern EU MS.

GRAPHICAL ABSTRACT



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ABSTRACT

The transition to a Circular Economy (CE) is a central pillar of the European Union (EU)'s sustainability agenda, yet significant heterogeneity persists among Member States (MS) in achieving this objective. This study contributes novel insights by introducing a dynamic efficiency assessment that simultaneously captures progress in the development of CE sectors, resource circularity and the reduction of material dependency across EU MS. Methodologically, a dynamic Data Envelopment Analysis (DEA) framework is employed, integrating two alternative efficiency specifications, complemented by Malmquist productivity indices (MPI) to evaluate intertemporal performance. The model accounts for potential frontier crossovers, thereby reflecting heterogeneous technological trajectories across EU countries. Results reveal marked disparities in CE efficiency transitions, with leading countries such as Germany, Italy, and the Netherlands displaying the highest efficiency scores, driven by effective policy frameworks. These findings highlight the urgency of coordinated actions to accelerate the CE transition across EU MS by fostering innovation and targeted policy incentives as critical levers for closing the identified efficiency gaps.

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1. Introduction

Global population growth and resource scarcity are projected to push consumption to the equivalent of three Earths by 2050 (UN, 2023), with resource use expected to double (OECD, 2019) and waste generation to rise by 70% (Kaza et al., 2018) underscoring the urgency of adopting a Circular Economy (CE) focused on reuse, repair, recycling, and product lifespan extension of materials and products (EC, 2020).

The CE, rooted in industrial ecology and the principle of "closing the loop" (Saavedra et al., 2018), is framed as a pathway to sustainable development, including not only environmental and economic dimensions but also social aspects (Mies and Gold, 2021). Its implementation depends on policy support, industry engagement, and supply chain design (MahmoumGonbadi et al., 2021).

The European Union (EU) has positioned itself as a leader in advancing the CE (Friant et al., 2021). The CE Action Plans launched in 2015 (EC, 2015) and 2020 (EC, 2020) are a core component of the European Green Deal (EC, 2019). These measures aim to establish a sustainable product policy framework, reduce waste, strengthen critical value chains, and consolidate EU leadership in CE sectors, enabling circular practices across numerous industries as a result of government policies and regulations (Mhatre et al., 2021). Notwithstanding the efforts made to accelerate the transition of the European economies towards the CE objectives, significant differences among EU Member States (MS) in terms of development of their CE sectors persist (De Oliveira Frascareli et al., 2024), highlighting the existence of a "two-speed Europe" (Mazur-Wierzbicka, 2021).

Despite the growing body of empirical studies on CE performance in the EU, most studies rely on static efficiency models or single-specification approaches that do not capture dynamic adjustments or trade-offs between the development of CE sectors and the country's material dependency. In addition, limited attention has been devoted to analysing efficiency frontier shifts and their institutional and operational determinants. This study addresses these gaps by adopting a dynamic Data Envelopment Analysis (DEA) framework with dual optimization and by integrating post-efficiency analysis to explain cross-country differences in CE transitions among the EU-27 MS from 2010 to 2021. Additionally, the analysis identifies the best-performing EU MS and explores the determinants shaping their CE efficiency paths towards increasing circular material use (CMU) and reducing material footprint (MF).

The contribution to existing literature is multiple. First, by applying a dynamic DEA framework that integrates both desirable and undesirable outputs and allows for potential frontier crossovers, it offers novel insights on the CE transition followed by EU MS. Specifically, results show significant disparities among EU MS in their CE transitions during the last decade and a limited capacity of most EU MS to reduce the MF of their production processes. Second, it conducts a post-efficiency analysis to identify factors and initiatives underpinning EU MS circular transitions. Third, results of the DEA efficiency models and the post-efficiency analysis provide updated insights to inform policymakers in designing effective strategies to accelerate CE transition in the EU and beyond.

The rest of the paper is organized as follows. Section 2 offers a review of recent studies assessing CE performance across European countries. Methodology and data are presented in Section 3. Results are shown in Section 4, followed by a discussion of the main findings and their policy implications (Section 5). Finally, last section provides some concluding remarks.

2. Literature review

The CE has evolved from early conceptualisations centred on resource loops and efficiency to encompass broader institutional, technological and social dimensions (Kirchherr et al., 2023). Despite this conceptual broadening, implementation remains constrained by regulatory inconsistencies, technological limitations and persistent behavioural lock-ins (Grafström and Aasma, 2021). Foundational reviews highlight the absence of an integrated conceptual architecture, which limits operationalization across supply chains and governance levels (Kalmykova et al., 2018). More recent analyses reinforce that structural, organisational and behavioural barriers continue to hinder progress from linear to CE models (Neves and Marques, 2022).

Institutional determinants have become central to explaining these uneven outcomes. Governance quality, political stability, and civic engagement significantly influence CE performance (Aldieri et al., 2025), while administrative capacity and institutional orientation shape environmental performance across Europe (Barra and Falcone, 2024a, 2024b). Policy frameworks also exert considerable influence: EU consumption-oriented regulations can reshape business models (Arranz and Arroyabe, 2023), although substantial heterogeneity persists across national CE strategies (Sanz-Torró et al., 2025). Such divergence reflects uneven institutional trajectories and governance bottlenecks (Nazarko et al., 2022). In parallel, macroeconomic modelling shows that realising CE ambitions requires structural adjustments and stronger material policy frameworks (Chepeliev et al., 2026).

Sectoral and thematic analyses further illustrate the complexity of CE transitions. Waste management remains a core research area, with calls for efficiency improvements (D'Adamo et al., 2024a) in light of rising global waste projections (Kaza et al., 2018). Specific challenges have also been examined in e-waste (Bressanelli et al., 2020), plastics and extended producer responsibility (Ramasubramanian et al., 2023), textiles (Reike et al., 2023), construction (Tavares and Pedroso, 2024) and metals (Hagelüken and Goldmann, 2022). Innovation and digitalization are increasingly recognized as key enablers: firm-level eco-innovation enhances circular performance (Cainelli et al., 2020), and targeted policy instruments support CE uptake among SMEs (Ren and Albrecht, 2023). Studies, such as those of Dey et al. (2022) and Lehmann et al. (2022), also emphasize the role of investment capabilities, managerial commitment, and innovation-oriented practices as strong predictors of CE adoption by European firms.

Yet despite advances across sectors and domains, significant implementation gaps persist. National experiences demonstrate the importance of long-term planning, coherent monitoring systems and multi-level governance arrangements (Ghisellini and Ulgiati, 2020). Regional analyses reveal pronounced heterogeneity in CE adoption, reflecting underlying structural and institutional disparities (Arsova et al., 2022), while alignment with broader sustainability agendas is considered essential to avoid fragmentation (UN, 2023). Moreover, innovation systems and institutional architectures vary considerably across EU MS, producing uneven CE development (Silvestri et al., 2020). Collectively, these findings depict CE transition as a structurally complex, institutionally mediated process constrained by fragmented conceptual frameworks and uneven governance capacities (European Court of Auditors, 2023).

In response to these challenges, environmental efficiency assessment has emerged as a core analytical strand. Indicators that capture national CE performance (Kristensen and Mosgaard, 2020) and enable cross-country comparisons (Marino and Pariso, 2020) have expanded rapidly. Comparative CE studies have proliferated (Claudio-Quiroga and Poza, 2024), alongside the increased use of multi-criteria decision-making methods (Dos Santos Gonçalves and Campos, 2022). Benchmarking exercises reveal substantial variability in CE outcomes: Lacko et al. (2021) identify heterogeneous performance across the Visegrád countries, and indicator-based assessments—including Eurostat's CE metrics (Eurostat, 2025), De Oliveira Frascareli et al. (2024) CE index, and the Grey Relational Analysis by Škrinjarić (2020)—consistently highlight gaps in material circularity across Europe. Such evidence calls for further research in the assessment of CE transitions among EU MS and the production of updated evidence to inform policymaking (D'Adamo et al., 2024b).

Within this expanding measurement landscape, efficiency analysis—particularly DEA—has become a leading methodological approach. DEA methods are well suited to CE assessment due to its ability to incorporate multiple inputs and desirable outputs (Thanassoulis, 2001) as well as combinations that include undesirable outputs (Sueyoshi and Goto, 2011). Applications span waste management efficiency (Expósito and Velasco, 2018) and country-level CE performance (Karsak and Ucar, 2024). Methodological extensions such as Malmquist Productivity Indices (MPI) (Banjerdpaiboon and Limleamthong, 2023), network DEA models (Ratner et al., 2025), and innovation-related efficiency frameworks (García Valderrama et al., 2024) further enhance the capacity to analyse CE's multidimensional dynamics. Zhu et al. (2022) illustrate how alternative optimization specifications within DEA can considerably alter country rankings and performance interpretations, underscoring the importance of methodological transparency.

Nevertheless, the literature on CE efficiency is dominated by static DEA models that inadequately capture transition dynamics, technological change, and structural heterogeneity across countries. Although some studies introduce dynamic elements (Banjerdpaiboon and Limleamthong, 2023; Ratner et al., 2025), efficiency is still typically assessed in relative terms, with limited linkage to structural determinants or policy implications. Results are also sensitive to variable selection, and the treatment of undesirable outputs remains partial (D'Adamo et al., 2024a; García Valderrama et al., 2024).

In this context, our contribution stresses the necessity of jointly modelling the economic expansion of CE sectors and their material implications. Existing assessments typically evaluate CE performance through composite indicators or efficiency scores focused on recycling, waste management, or eco-innovation, yet they do not explicitly examine whether increases in the gross value added (GVA) of CE sectors simultaneously lead to higher CMU and a reduction in MF. This study argues that CE efficiency should be framed as a multidimensional optimization problem in which sectoral growth enhances circularity while reducing dependence on primary resource inputs. This dual requirement has not been explicitly operationalized in prior CE efficiency analyses.

Additionally, several prior studies incorporate contextual or policy variables directly into DEA models instead of treating them as post-efficiency determinants (e.g., governance or policy variables in Ratner et al., 2025; policy assessment dimensions in Sanz-Torró et al., 2025), potentially weakening the interpretability of their results.

In response to these limitations, present study contributes to CE efficiency assessment literature by applying a dynamic output-oriented DEA model that incorporates a dual optimization specification (Sueyoshi and Goto, 2011). This approach integrates desirable and undesirable outputs and allows for frontier crossovers over time, providing a more nuanced representation of circular efficiency performance and novel implications for policy making. The analysis is further complemented by a post-efficiency assessment examining the role played by specific drivers, such as resource productivity and waste management and recycling rates, in shaping CE performance, thereby strengthening the model's explanatory power and its relevance for more effective policy design.

3. Method and materials

In the context of CE transitions, DEA models have been widely used as they allow the evaluation of multiple input and output variables simultaneously in the absence of explicit production functions. The novel approach proposed in this study assesses each EU MS's capacity to generate desirable outputs—namely, GVA of CE sectors and CMU—and undesirable outputs, measured by MF, from a given set of inputs, including labour and investment in CE-related activities. To the best of our knowledge, the dual optimization framework adopted in this study represents a novel contribution to the existing literature in this field. Furthermore, the integration of a dynamic window approach and MPI to capture temporal adjustments and technological change—both essential for analysing long-term transition processes—together with a post-efficiency analysis to identify the factors driving CE efficiency trajectories among EU MS, further strengthens the methodological contribution of this research. DEA models can be input- or output-oriented, depending on the specific objective pursued. In the context of this study, which focuses on the circularity performance of a group of decision-making units or DMUs (i.e., EU MS), an output-oriented model has been considered the appropriate approach.

A description of input and output variables is provided in Table 1. Recent DEA applications have emphasized the importance of incorporating undesirable outputs to create more realistic and comprehensive models (Expósito and Velasco, 2018).

Following the developments proposed by Sueyoshi and Goto (2011, 2017), the methodology employed is based on a radial model to determine a relative efficiency indicator for each DMU. An inefficient unit is projected toward the efficiency frontier in a radial direction, employing two different efficiency specifications. The first specification assumes that the DMU can reduce (or maintain) its inputs to increase desirable outputs while reducing (or maintaining) undesirable outputs. The second specification allows for an increase (or maintenance) of inputs in order to reduce undesirable outputs while increasing (or maintaining) desirable outputs. Accordingly, the first specification prioritizes maximizing GVA of CE sectors and CMU rate (as desirable outputs), and secondarily minimizing MF (as undesirable output). Conversely, the second specification prioritizes minimizing undesirable outputs, even if desirable outputs remain constant. Each specification produces an autonomous unified efficiency (UE) score, referred to as 'Natural Efficiency' and 'Managerial Efficiency', respectively. The proposed analytical framework is illustrated in Fig. 1. Incoming arrows in the central block indicate model inputs, while outgoing arrows indicate model outputs.

The methodological framework considers $n = 27$ DMUs (EU MS) that use $m = 2$ inputs to produce $s = 2$ desirable outputs and $h = 1$ undesirable output. Each region uses a column vector of inputs, X_j $(j = 1, \ldots, n)$, to generate a column vector of desirable outputs, G_j, and a column vector of undesirable outputs, B_j, with the assumption that $X_j > 0$, $G_j > 0$, and $B_j > 0$ for each j $(j = 1, \ldots, n)$ (1). The intensity or structural variables are expressed as $\lambda = (\lambda_1, \ldots, \lambda_n)^T$, which are unknown and used to link inputs and outputs through a convex combination (2)-(4).

Table 1
Definition of variables used in the DEA and the post-efficiency analysis.

DEA analysis	
Inputs	**Description**
Investment in CE sectors	Gross investment in tangible goods in millions of euros in the CE sectors during the reference year
Employment in CE sectors	Number of persons employed in the CE sectors. Jobs are expressed in full-time equivalent employed persons
Outputs	**Description**
GVA of CE sectors	GVA at factor cost, in millions of euros, in the CE sectors, being the gross income from operating activities after adjusting for operating subsidies and indirect taxes
CMU rate	Share of material recovered and fed back into the economy in overall material use (measured as a percentage)
MF	Amount of raw materials needed (or, the amount of extraction, domestic and abroad, required directly and indirectly) to produce the products consumed in the country (measured in tonnes per capita). This indicator also illustrates material dependency of an economy's productive structure
Post-efficiency analysis	
Factors	**Description**
GDP pc	GDP per person (in Euros per capita)
Waste pc	Generated waste per person (in kilograms per capita)
Recycling rate	Recycled waste of total waste treated (measured in percentage)
Resource productivity	GDP divided by domestic material consumption (in Euros per kilogram)

Source: Eurostat (2025).

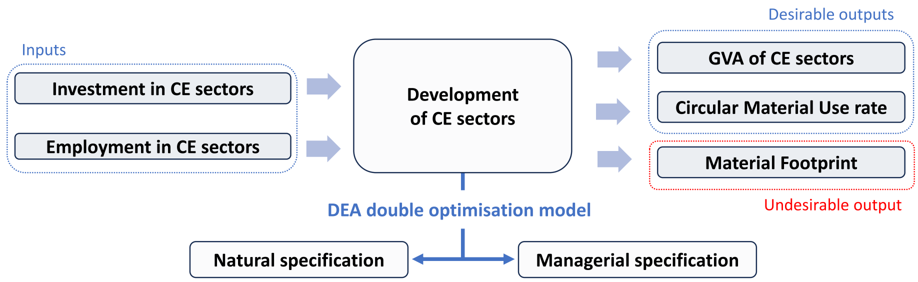

Fig. 1. DEA analytical framework.
Source: Own elaboration.

$$\text{Max } \xi + \varepsilon\left[\sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b\right] \tag{1}$$

subject to (2)-(4),

$$\sum_{j=1}^{n} x_{ij}\lambda_j + (-1)^o d_i^x = x_{ik}(i=1,\dots,m), \tag{2}$$

$$\sum_{j=1}^{n} g_{rj}\lambda_j \text{-} d_r^g \text{-} \xi g_{rk} = g_{rk}(r=1,\dots,s), \tag{3}$$

$$\sum_{j=1}^{n} b_{fj}\lambda_j + d_f^b + \xi b_{fk} = b_{fk}(f=1,\dots,h), \tag{4}$$

$$\lambda_j \geq 0(j=1,\dots,n), \xi : URS, d_i^x \geq 0\ (i=1,\dots,m), d_r^g \geq 0\ (r=1,\dots,s)\ and\ d_f^b \geq 0\ (f=1,\dots,h)$$

The UE score θ^* for each DMU k is given by (5):

$$\theta^* = 1 \text{ - } \left[\xi^* + \varepsilon\left(\sum_{i=1}^{m} R_i^x d_i^{x^*} + \sum_{r=1}^{s} R_r^g d_r^{g^*} + \sum_{f=1}^{h} R_f^b d_f^{b^*}\right)\right] \tag{5}$$

When $o = 0$, the model follows the first specification, whereas $o = 1$ corresponds to the second specification. The notation ξ: URS indicates that ξ is unrestricted.

For instance, if $o = 0$, the first constraint written as (6):

$$\sum_{j=1}^{n} x_{ij}\lambda_j = x_{ik} - d_i^x, \tag{6}$$

indicates that the DMU must reduce its input i, x_{ik}, the amount of d_i^x, in order to reach the efficient frontier.

Likewise, the second constraint, written as (7):

$$\sum_{j=1}^{n} g_{rj}\ \lambda_j = g_{rk} + \xi\ g_{rk}\ + d_r^g, \tag{7}$$

indicates that the DMU has to increase its output r, g_{rk}, the quantity of $\xi\ g_{rk}$ in the radial movement and d_r^g value in slack, in order to reach the efficiency frontier. Similarly for the third restriction. The fourth constraint gives us the convex combination of structural variables.

Additionally, this DEA approach allows estimated efficiency frontiers to change over time and examines how much an efficiency score changes by shifting a combination of adjacent periods, often referred to as a "window". When shifts occur between frontiers, window analysis aggregates data from several successive periods into a single "window" within which a new efficiency frontier is estimated. As a result, efficiency scores are smoothed across time by benchmarking each observation against the newly determined frontier for its respective window.

This DEA approach further allows for the evaluation of intertemporal variations in relative efficiency by applying MPI (Sueyoshi et al., 2017). These indices are calculated across different time periods or temporal "windows," facilitating the analysis of both medium- and long-term trends in performance. MPIs provide valuable insights into how each country progresses toward the defined objectives when benchmarked against other nations.

Despite the extensive application of DEA in efficiency measurement, certain limitations must be acknowledged. DEA models generally do not account for random errors, although recent advances in probabilistic and Bayesian DEA models aim to incorporate statistical noise into the efficiency frontier estimation. Moreover, DEA assumes that all DMUs operate under similar conditions, which may not be realistic in cases of highly heterogeneous units with different legal or socio-economic frameworks. In this specific case, a constant returns-to-scale model was adopted to better address regional differences regardless of size.

Subsequent to the DEA efficiency assessment, a post-estimation analysis is carried out with the aim to unveil explanatory factors to efficiency (both natural and managerial) differences among EU MS. Specifically, and based on the existing literature, variables such as gross domestic product (GDP) per capita, generated waste per capita, recycle rate, and resource productivity, have been tested in alternative panel-data regression models. All variables were log-transformed to mitigate heteroskedasticity issues. Pesaran tests indicate that panels are cross-sectional dependent. To address these concerns, the second-stage analysis employs Feasible Generalised Least Squares (FGLS), which accounts for autocorrelation within panels as well as cross-sectional correlation and heteroskedasticity across panels.

Data have been gathered from Eurostat database on CE indicators for the 27 EU MS and the period 2010-2021 (Eurostat, 2025). As defined by Eurostat, CE sectors are the recycling sector, the repair and reuse sector, and the rental and leasing sector. A description of the variables used in this study is shown in Table 1. Basic descriptive statistics are shown in Tables 2 and 3.

Finally, it is worth noting that minimum sample size and variable correlation requirements, as established by Thanassoulis (2001), are appropriately met. Despite DEA models do not generally establish causal relationships between variables, Granger non-causality tests (Juodis et al., 2021) have been performed confirming causality between inputs and outputs.

Table 2
Descriptive statistics of DEA model variables (inputs and outputs).

	Investment CE	Employment CE	GVA CE	CMU rate	MF
Average	3266.23	136,461.16	8479.18	8.64	18.29
Std. deviation	5701.96	190,100.77	14,501.57	6.25	8.03
Maximum	34,489.00	785,297.00	79,177.00	29.00	54.71
Minimum	33.00	1643.00	132.00	1.20	7.93

Source: Own elaboration based on Eurostat database

Table 3
Descriptive statistics of post-efficiency analysis variables.

	GDP pc	Waste pc	Recycling rate	Resource productivity
Average	28,110.98	497.41	35.81	1.86
Std. deviation	19,363.41	132.50	15.28	0.82
Maximum	99,360	862	70.3	4.73
Minimum	5960	247	8.3	0.62

Source: Own elaboration based on Eurostat database

4. Results

DEA estimation results are shown in Table 4 (natural specification) and 5 (managerial specification). UE estimates show that the number of efficient (UE = 1) countries is higher in the case of the natural specification, since the managerial specification prioritizes the reduction of the material dependency (MF). Specifically, Germany, Italy, and Netherlands outperform as efficient countries in both model specifications. Therefore, these three countries can be identified as benchmark DMUs. Additionally, it is also worth noting that the number of efficient countries slightly increases in the analysed period under the natural specification. Countries such as Belgium, Spain, Cyprus, and Luxembourg register full-efficiency scores (UE = 1) in the second part of the period. This finding suggests a rightward shift of the efficiency frontier (i.e., as the result of technological upgrading), thus significantly increasing the capacity of these countries to attain higher efficiency levels. This finding is not observed in the case of the managerial specification, where efficient countries remain more stable during the analysed period.

When the priority focuses on the reduction of the MF (i.e., managerial specification), UE scores are generally much lower (Table 5). Interestingly, countries such as Ireland, Luxembourg, and Slovenia, which showed to be highly efficient under the natural specification, now register significantly lower efficiency scores. Only a reduced group of countries is able to reach full efficiency (i.e., Germany, Italy, and the Netherlands). The case of France is worth noting since while it registers high and full efficiency scores during the first years (2011-2016), efficiency declines in subsequent years.

With the aim of identifying those countries observing a potential shift of their efficiency frontiers, MPIs have been estimated. When the MPI registers a value higher than unity, it indicates the occurrence of a frontier shift due to a technology development and/or a managerial improvement (Sueyoshi et al., 2017). In contrast, the opposite case can be found if UE is equal to or less than unity. Figs. 2 and 3 summarize the relationship between MPIs and UE average estimates in the analysed period, measured under both natural and managerial specifications, and under the assumption that a crossover of efficiency frontiers might have occurred in the observed period (2010-2021). Although all EU MS have been making efforts to accelerate circular transition of their production processes, the degree and speed of technology and/or managerial innovation have been relatively modest in most countries, as shown by the low MPI estimates. Nevertheless, both figures illustrate that less efficient economies (such as Cyprus, Portugal, and Romania) show a clear path towards convergence with most efficient countries. This can be observed by the higher MPI values estimated for these less efficient countries. Additionally, findings reinforce the existence of frontier crossovers as less efficient countries incorporate more advanced technologies and managerial practices in their CE sectors.

4.1. Robustness analysis

With the aim to test the robustness of the proposed efficiency assessment to different temporal windows, the full range of window-lengths (i.e., from two-year to ten-year) has been estimated. As example, Table 6 shows the average values of UE and MPI estimates by using a 3-year window DEA analysis with frontier crossover, thus assuming that a EU MS in the t period can access new technologies and managerial innovations in the previous two periods. Results show no significant differences from those obtained previously. This analysis has been run for the full spectrum of window lengths, showing a high degree

Table 4
UE scores under the natural DEA specification.

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Belgium	0.879	0.969	0.981	0.997	0.984	**1.000**	**1.000**	0.991	**1.000**	**1.000**	0.992
Bulgaria	0.284	0.289	0.374	0.386	0.417	0.547	0.449	0.253	0.309	0.346	0.249
Czechia	0.633	0.767	0.756	0.795	0.782	0.817	0.870	0.836	0.751	0.780	0.667
Denmark	0.578	0.551	0.645	0.753	0.707	0.714	0.648	0.659	0.579	0.628	0.593
Germany	0.986	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
Estonia	0.940	**1.000**	0.937	0.987	0.970	**1.000**	0.962	0.955	0.928	0.796	0.845
Ireland	**1.000**	0.999	**1.000**	**1.000**	**1.000**	**1.000**	0.988	**1.000**	0.988	**1.000**	**1.000**
Greece	0.188	0.359	0.360	0.190	0.242	0.306	0.405	0.515	0.449	0.795	0.905
Spain	0.982	0.931	0.821	0.723	0.680	0.681	0.885	0.935	**1.000**	**1.000**	0.993
France	0.997	**1.000**	**1.000**	**1.000**	**1.000**	0.927	0.911	0.902	0.856	0.866	0.825
Croatia	0.389	0.561	0.571	0.764	0.705	0.700	0.714	0.611	0.562	0.538	0.496
Italy	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	0.998	**1.000**	**1.000**	0.997
Cyprus	0.160	0.235	0.358	0.599	0.457	0.409	0.333	0.324	0.562	**1.000**	**1.000**
Latvia	0.437	0.207	0.516	0.715	0.724	0.874	0.696	0.492	0.376	0.344	0.249
Lithuania	0.493	0.544	0.396	0.490	0.580	0.553	0.459	0.409	0.312	0.251	0.206
Luxemb.	0.917	0.990	0.933	0.893	**1.000**	0.941	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
Hungary	0.950	1.000	0.905	0.665	0.695	0.766	0.747	0.663	0.459	0.440	0.384
Malta	0.827	0.645	0.856	**1.000**	0.747	0.861	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
Netherlands	0.986	**1.000**	**1.000**	**1.000**	0.970	**1.000**	0.995	0.967	0.997	**1.000**	**1.000**
Austria	0.539	0.597	0.657	0.728	0.782	0.824	0.814	0.774	0.713	0.736	0.667
Poland	0.693	0.884	0.884	0.828	0.711	0.780	0.744	0.580	0.624	0.577	0.547
Portugal	0.131	0.223	0.223	0.134	0.119	0.117	0.106	0.120	0.153	0.152	0.128
Romania	0.179	0.268	0.232	0.091	0.066	0.077	0.107	0.154	0.123	0.116	0.114
Slovenia	0.864	**1.000**	**1.000**	0.927	**1.000**	**1.000**	**1.000**	0.893	0.714	**1.000**	**1.000**
Slovakia	0.644	0.644	0.653	0.674	0.693	0.693	0.664	0.525	0.696	0.697	0.568
Finland	0.495	0.546	0.374	0.330	0.317	0.245	0.340	0.306	0.282	0.583	0.782
Sweden	0.539	0.619	0.588	0.551	0.482	0.440	0.545	0.575	0.543	0.603	0.619
Average	0.656	0.697	0.704	0.712	0.697	0.714	0.718	0.683	0.666	0.713	0.697
Std. Dev.	0.301	0.293	0.270	0.284	0.283	0.286	0.284	0.290	0.290	0.290	0.310

Source: Own elaboration

Table 5
UE scores under the managerial DEA specification.

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Belgium	0.643	0.690	0.671	0.628	0.629	0.589	0.615	0.597	0.729	0.758	0.681
Bulgaria	0.148	0.128	0.130	0.124	0.128	0.144	0.123	0.087	0.137	0.169	0.122
Czechia	0.321	0.347	0.313	0.293	0.281	0.269	0.287	0.322	0.370	0.406	0.326
Denmark	0.296	0.246	0.261	0.283	0.247	0.212	0.213	0.223	0.217	0.221	0.225
Germany	0.967	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
Estonia	0.405	0.437	0.328	0.279	0.270	0.244	0.221	0.236	0.314	0.330	0.369
Ireland	0.377	0.378	0.341	0.318	0.351	0.288	0.266	0.248	0.200	0.227	0.268
Greece	0.156	0.128	0.111	0.091	0.106	0.119	0.135	0.162	0.189	0.228	0.259
Spain	0.858	0.901	0.840	0.751	0.729	0.722	0.746	0.698	0.763	0.725	0.727
France	0.981	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	0.935	0.890	0.861	0.933	0.840
Croatia	0.174	0.211	0.204	0.260	0.220	0.192	0.202	0.204	0.243	0.253	0.244
Italy	0.977	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	0.936
Cyprus	0.059	0.074	0.106	0.096	0.103	0.078	0.066	0.082	0.103	0.125	0.160
Latvia	0.169	0.083	0.170	0.219	0.205	0.231	0.175	0.151	0.176	0.184	0.149
Lithuania	0.192	0.191	0.126	0.144	0.163	0.140	0.121	0.121	0.127	0.120	0.104
Luxemb.	0.434	0.382	0.300	0.229	0.181	0.124	0.171	0.203	0.210	0.210	0.171
Hungary	0.565	0.552	0.424	0.292	0.311	0.313	0.289	0.267	0.233	0.238	0.219
Malta	0.264	0.233	0.302	0.319	0.206	0.183	0.295	0.396	0.578	0.674	0.767
Netherlands	**1.000**	**1.000**	**1.000**	**1.000**	0.965	**1.000**	0.992	0.954	**1.000**	**1.000**	**1.000**
Austria	0.274	0.294	0.304	0.306	0.331	0.297	0.305	0.293	0.315	0.318	0.275
Poland	0.597	0.633	0.615	0.607	0.575	0.510	0.472	0.464	0.447	0.405	0.403
Portugal	0.149	0.148	0.164	0.139	0.126	0.122	0.108	0.118	0.117	0.124	0.108
Romania	0.165	0.155	0.133	0.111	0.078	0.073	0.079	0.069	0.054	0.047	0.047
Slovenia	0.318	0.385	0.340	0.294	0.319	0.285	0.294	0.287	0.355	0.337	0.231
Slovakia	0.287	0.258	0.251	0.245	0.243	0.208	0.197	0.182	0.351	0.434	0.397
Finland	0.188	0.179	0.104	0.085	0.085	0.059	0.070	0.068	0.074	0.066	0.070
Sweden	0.303	0.310	0.251	0.226	0.229	0.201	0.216	0.192	0.197	0.206	0.240
Average	0.417	0.420	0.400	0.383	0.373	0.356	0.355	0.352	0.384	0.398	0.383
Std. Dev.	0.298	0.313	0.309	0.307	0.306	0.313	0.308	0.299	0.305	0.308	0.302

Source: Own elaboration

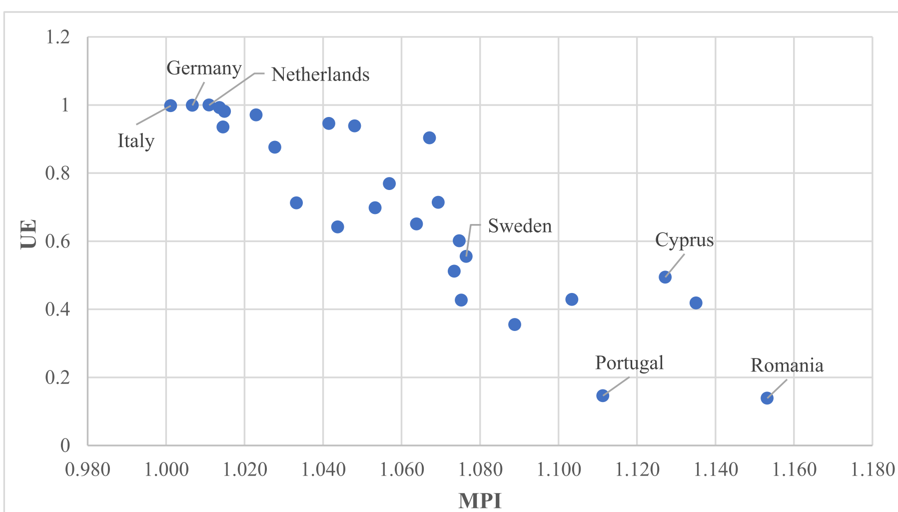

Fig. 2. Relationship between UE average scores and MPI average indices under the natural DEA specification.
Source: Own elaboration.

of robustness in the findings. In every case the number of efficient countries under the natural specification is significantly higher than under the managerial specification. Specifically, Germany, Italy, the Netherlands, and to a lesser extent France, are the most efficient countries, showing a capacity to reduce the MF in their production processes (i.e., reduction of material dependency) at the same time that they are able to maximise GVA of CE sectors and CMU rates. As shown by the MPI estimates, frontier crossovers are modest in most countries. Countries, such as Bulgaria, Latvia, Lithuania, and Portugal show higher MPI estimates under the natural specification. Under a managerial specification, MPI estimates are generally lower, with Germany and Portugal being the only countries showing a modest MPI above 1.1.

Once efficiency scores are estimated, a post-estimation analysis using FGLS panel-data models is carried out with the aim to explore the impact of certain explanatory variables on the estimated efficiency scores under both DEA specifications (Table 7). Results reveal that natural efficiency estimates are significantly determined by GDP per capita and resource productivity, thus higher levels of both variables lead to higher efficiency scores among EU MS in the analysed period (2010-2021). These impacts are also confirmed in the case of the managerial efficiency estimates. Interestingly, the variables ‘waste per capita’ and ‘recycling rate’ only impact managerial efficiency, showing that higher levels of water per capita reduce managerial efficiency and higher recycling rates increase it. Consequently, findings show that natural efficiency is highly

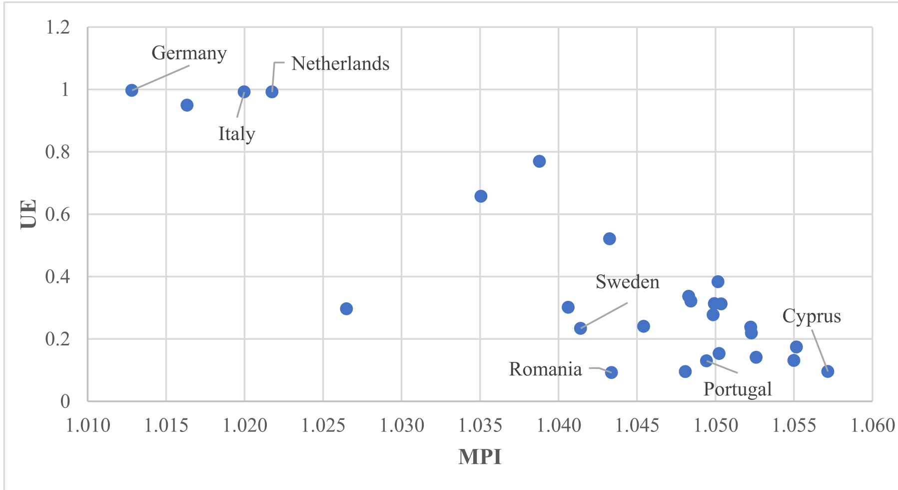

Fig. 3. Relationship between UE average scores and MPI average indices under the managerial DEA specification.
Source: Own elaboration.

Table 6
Average values of estimated UE scores and MPI under natural and managerial DEA specifications (3-year window analysis).

	Natural			Managerial
	UE	MPI	UE	MPI
Belgium	0.984	1.026	0.649	1.059
Bulgaria	0.302	1.125	0.116	1.092
Czechia	0.763	1.067	0.319	1.082
Denmark	0.628	1.089	0.235	1.073
Germany	1.000	0.996	1.000	1.113
Estonia	0.942	1.084	0.328	1.068
Ireland	1.000	0.985	0.311	1.085
Greece	0.506	1.058	0.164	1.097
Spain	0.885	1.000	0.764	1.072
France	0.932	1.039	0.933	1.069
Croatia	0.593	1.063	0.220	1.083
Italy	0.999	1.034	0.984	1.079
Cyprus	0.504	1.088	0.105	1.080
Latvia	0.418	1.161	0.147	1.082
Lithuania	0.435	1.129	0.145	1.080
Luxemb.	0.998	0.986	0.234	1.071
Hungary	0.686	1.076	0.337	1.082
Malta	0.848	1.127	0.400	1.062
Netherlands	0.984	1.014	0.980	1.044
Austria	0.705	1.075	0.298	1.068
Poland	0.680	1.022	0.519	1.078
Portugal	0.147	1.188	0.125	1.111
Romania	0.151	0.977	0.087	1.085
Slovenia	0.973	1.047	0.305	1.071
Slovakia	0.608	1.127	0.270	1.077
Finland	0.488	0.988	0.100	1.088
Sweden	0.574	1.047	0.243	1.078
Average	0.694	1.060	0.382	1.079
Std. Dev.	0.266	0.057	0.298	0.014

Source: Own elaboration

Table 7
Post-efficiency analysis for both DEA specifications.

Variable	Natural		Managerial	
	Relation	*p-value*	Relation	*p-value*
GDP per capita	Positive	0.003***	Positive	0.005***
Waste per capita	Negative	0.948	Negative	0.002***
Recycling rate	Positive	0.390	Positive	0.019**
Resource productivity	Positive	0.000***	Positive	0.000***
Wald Chi2	*66.97****		*222.05****	

Note: *** Denotes significance at 1%.,** at 5%, and * at 10%.
Source: Own elaboration

determined by purely economic variables, while managerial efficiency (and the country's capacity to reduce its material dependency) is significantly impacted by operational variables, such as the level of recycling and waste generation in the country.

5. Discussion

Consistent with prior studies, the results confirm significant cross-country disparities in advancing CE transitions among EU MS (Ratner et al., 2025). The higher number of efficient countries under the natural specification (compared to the managerial specification) indicates that EU MS have been more effective in expanding the GVA of the CE sectors and CMU rates than in reducing material dependency. This asymmetry suggests strategies that favour sectoral growth without equivalent reductions in material consumption. Further, MPI estimates reveal limited frontier shifts, pointing to improvements mainly derived from input–output adjustments rather than disruptive innovation, which would require greater investments in R&D and technological capacity (Kumar et al., 2025). These findings contrast with more optimistic interpretations based on composite efficiency indices (De Oliveira Frascareli et al., 2024) and highlights the persistence of material dependency across Europe, as shown by the significantly lower efficiencies achieved under the managerial specification for most EU MS.

The identification of the Netherlands, Germany, and Italy as full-efficiency DMUs under both model specifications is consistent with existing literature (Lacko et al., 2021). Previous studies frequently rank the Netherlands and Germany at (or) near the efficiency frontier, highlighting their strong resource productivity, advanced waste management systems, technological capacity, and mature policy frameworks (Karsak and Ucar, 2024). Italy has also been recognized as a high performer, particularly in recycling and waste efficiency (D'Adamo et al., 2024a; García Valderrama et al., 2024), although earlier static DEA applications sometimes reported near-efficiency rather than full efficiency (Nazarko et al., 2022).

Existing EU policies effectively promote recycling and secondary material markets (D'Adamo et al., 2024a), but they are less successful in achieving absolute reductions in MF (Banjerdpaiboon and Limleamthong, 2023). Only a few EU MS perform efficiently when MF reduction is prioritized (i.e., Germany, followed closely by the Netherlands and Italy), indicating limited alignment with resource sufficiency goals. Post-efficiency analysis shows that this MF related efficiency (i.e., managerial efficiency) is positively influenced by higher resource productivities and more advanced recycling processes.

In this context, the present results not only confirm the established leadership of the Netherlands and Germany but also provide stronger evidence of Italy's sustained performance. The robustness of full efficiency across both specifications suggests that a dynamic dual-optimization approach may better capture persistent structural advantages and long-term policy effectiveness than short-term fluctuations observed in more restrictive or static models (Ratner et al., 2025).

Their experiences provide valuable insights for shaping strategies in less advanced EU MS. Table 8 summarizes the main initiatives taken by these benchmark countries to develop their CE sectors, while augmenting CMU rates and reducing material dependency.

These benchmark countries exemplify distinct but highly effective CE strategies, achieving substantial progress in their circularity objectives. The Netherlands stands out with its ambitious target of becoming fully circular by 2050 (PBL Netherlands Environmental Assessment Agency, 2023), Germany emphasizes innovation, efficiency, and regulation-driven waste reduction (EEA, 2022), and Italy advances through eco-design and recycling policies (Ministero della Transizione Ecologica, 2022). Key success factors shared by these three countries include the early adoption of CE strategies and ambitious national targets, complemented by high resource productivity and recycling rates—Germany leading in recycling in 2022, and the Netherlands leading in resource productivity (EEA, 2024), whereas in Italy, reuse has steadily increased over the last years (Ghisellini and Ulgiati, 2020).

Table 8
Main CE initiatives identified in the most efficient countries under both DEA specifications.

	Netherlands	Italy	Germany
Innovation support: Funding for the development of circular technologies and sustainable business models	•	•	•
Application of advanced technologies: Using artificial intelligence and other disruptive technologies to achieve a greenhouse gas-neutral CE	•		•
Eco-design promotion: Developing lifecycle assessment tools to minimize raw material consumption and enhance advanced recycling	•	•	•
Financial support programs: Initiatives to facilitate the transition to a CE through economic incentives	•	•	•
Product-related policies: Implementation of R-strategies (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover)	•	•	•
Regional strategies: Adapting the CE to local needs with tailored approaches in different regions	•	•	•
Environmental criteria for public procurement: Establishing minimum ecological requirements for government purchases		•	
Tax incentives: Financial benefits for companies adopting circular production models	•	•	•
Repair bonuses: Initiatives to reduce waste by encouraging the repair of electrical and electronic equipment			•
Smart urban districts: Creating city zones that facilitate circular solutions	•	•	•
Environmental impact assessment: Using the Product Environmental Footprint method to measure and communicate the ecological footprint of products, promoting eco-labelling	•	•	•
Stricter regulations: More rigorous policies in sectors such as textiles, hazardous waste, and microplastic reduction in bio-waste	•	•	•

Source: Authors' elaboration

By contrast, countries such as Romania, Lithuania, Latvia, and Cyprus remain low performers, particularly under the managerial efficiency specification. Structural challenges, such as limited capital, weaker institutions, and reliance on resource-intensive sectors, hinder their progress in their CE transitions. These countries exhibit lower recycling rates and resource productivity levels compared to benchmark countries. Nevertheless, most less efficient countries report MPI values above one, signalling gradual efficiency improvements and convergence with most efficient countries.

Overall, ambitious CE initiatives, such as those shown in Table 8, demonstrate clear strategic goals and targeted efforts to overcome these challenges and accelerate CE development (Morseletto, 2020). Bridging efficiency gaps among EU MS requires policies that intensify technological innovation, foster specialized human capital, and incentivize resource-use reduction (Hartley et al., 2020). Successful strategies also depend on cooperation among EU MS to facilitate knowledge transfer and on stimulating pro-environmental behaviours among businesses and citizens (Kirchherr et al., 2018). Consistent with previous studies, CE performance aligns with economic and technological development, with advanced economies such as Germany and the Netherlands better positioned to meet EU targets, a reality that policymakers must take into account (European Court of Auditors, 2023).

5.1. Policy implications

The transition to a CE constitutes an EU strategic priority to reduce its material dependency from external territories (EC, 2020). Lessons from frontrunner countries, such as Germany, the Netherlands and Italy, highlight the effectiveness of ambitious, well-coordinated CE strategies supported by regulation (Arranz and Arroyabe, 2023), innovation incentives (Ren and Albrecht, 2023), and transformative innovation policies (Falcone and Tutore, 2025). Nevertheless, and due to its multidimensional nature—spanning technological, market, institutional, and cultural domains—the CE transition faces significant operational barriers (Grafström and Aasma, 2021). The findings of this study yield several implications for reducing these barriers and strengthening this CE transition in EU MS.

First, the divergence between natural and managerial efficiency underscores the need for EU and national policies to move beyond a growth-oriented conception of the CE. Current policy frameworks, including the EU CE Action Plan, have been effective in stimulating recycling activities and market development for secondary materials, but appear less effective in incentivising absolute reductions in MF. The finding that only a small group of EU MS achieve high efficiency when MF reduction is prioritized suggests that policy instruments remain unevenly aligned with resource sufficiency objectives.

To address this gap, EU policymakers should reinforce regulatory and economic instruments that explicitly target material demand reduction, such as strengthened eco-design requirements, durability and reparability standards, and consumption-oriented measures. Several new legislative initiatives, such as the Ecodesign Directive, the Corporate Responsibility Directive, the Green Claims Directive, and the Directive on the Right to Repair, are expected to effectively impact CMU and MF rates of EU MS.

Second, the pronounced heterogeneity in CE efficiency across EU MS calls for a more differentiated and context-sensitive policy approach (D'Adamo et al., 2022). The results confirm the existence of a "two-speed" CE transition, where more advanced economies benefit from higher resource productivity, stronger institutional capacity, and more mature CE sectors, while less efficient countries face structural and financial constraints (Domenech and Bahn-Walkowiak, 2019). Further, resource circularity shows uneven development across industrial sectors. Recycling-driven growth is most visible in construction, metals, and packaging sectors, while electronics and automotive struggle with material loop closure, underscoring the need for targeted initiatives (Reuter et al., 2019).

In this context, EU-level coordination mechanisms should be strengthened to support lagging EU MS through targeted funding, technical assistance, and policy learning (De Pascale et al., 2023). Instruments such as cohesion policy funds, the Recovery and Resilience Facility, and dedicated CE investment programmes could be more explicitly linked to material efficiency outcomes and circularity improvements in specific sectors.

Third, the post-efficiency analysis highlights that managerial efficiency—closely associated with reductions in MF—is significantly influenced by operational factors, including waste generation per capita and recycling performance. This finding suggests that CE policy effectiveness depends not only on macroeconomic conditions but also on the quality of cost-effective supply of secondary raw materials, waste management systems, and organisational practices within CE businesses.

Accordingly, policymakers should prioritise investments in waste prevention and high-quality recycling systems, particularly in countries where waste generation remains high (Chioatto and Sospiro, 2023). Further, strengthening extended producer responsibility schemes (Ramasubramanian et al., 2023), improving separate collection systems (Ellen MacArthur Foundation, 2021), green procurement (Wijayasundara et al., 2022), fiscal incentives (De Sa and Korinek, 2021), eco-design standards (Reike et al., 2018), digital product passports (Reuter et al., 2019), and fostering markets for high-value secondary materials can enhance managerial efficiency and accelerate material loop closure. As noted by Velenturf and Purnell (2021), these policy initiatives would help to reduce material dependency and to enhance resource productivity across sectors.

Importantly, such measures require coherent multi-level governance, ensuring alignment between EU directives, national strategies, and local implementation capacities (Camilleri, 2020). Lastly, maximizing impact and ensuring long-term sustainability depend on the development and implementation of these initiatives in close collaboration with businesses and social platforms (e.g., the European CE Stakeholder Platform).

6. Conclusions

The CE transition is widely recognized as an essential pathway to achieving environmental sustainability and resource resilience across the EU. The unique findings of this study make multiple contributions to the existing literature. First, it introduces a dynamic dual-specification DEA framework that captures trade-offs between economic performance and material dependency, allowing for efficiency frontier crossovers. Second, it provides updated empirical evidence on CE efficiency dynamics in the EU-27 over more than a decade, revealing persistent structural asymmetries. The observed asymmetry between natural and managerial efficiency show that EU countries tend to prioritise sectoral growth over absolute resource reduction. Similarly, the identification of Germany, Italy, and the Netherlands as benchmark countries aligns with earlier studies. In contrast, most EU MS show persistent inefficiencies, despite signs of gradual convergence. Third, unlike static assessments, the dynamic analysis reveals limited frontier shifts in most EU MS, suggesting that recent improvements are driven mainly by incremental adjustments rather than structural innovation. Fourth, by integrating post-efficiency analysis, it identifies distinct economic and operational drivers of CE efficiency, offering actionable insights for differentiated policy design.

While the methodological approach adopted in this study provides a comprehensive assessment of CE performance dynamics, some limitations must be acknowledged. DEA remains a deterministic method and does not consider statistical noise or external shocks that may influence performance results. In addition, the study relies on the availability of harmonized CE indicators at the national level, which may not fully reflect sectoral or regional heterogeneity within countries. Future research could therefore integrate stochastic DEA methods or spatial modelling to better account for uncertainty and interdependencies among countries. Likewise, expanding the analytical scope to sectoral or subnational scales would provide insights into territorial inequalities and localised transition dynamics. Further work should also examine the role of governance capacity, financial mechanisms and social engagement in sustaining CE progress over time. Overall, this study contributes valuable evidence on the heterogeneous evolution of CE performance in the EU and highlights the efforts still required to achieve a more efficient circular transition.

CRediT authorship contribution statement

Isabel Álvarez: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Alfonso Expósito:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Daniel Sánchez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Francisco Velasco:** Writing – review & editing, Software, Methodology, Formal analysis.

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.

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Data availability

Data will be made available on request.

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