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Insight into territorial efficiency of circular economy through data envelopment analysis

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Introduction: The circular economy (CE) has emerged as a key paradigm for promoting sustainable economic development by enhancing resource efficiency, minimizing waste, and reducing environmental harm. Despite its widespread adoption in policy frameworks, the practical implementation and efficiency of CE strategies across countries remain insufficiently evaluated.

Methods: This study employs a methodological approach based on Data Envelopment Analysis (DEA) to assess the territorial efficiency of CE implementation across 27 European Union (EU) countries. A composite indicator was constructed using relevant CE metrics obtained from Eurostat, enabling a comparative analysis of national performance in achieving circularity.

Results: The findings reveal significant variation in CE efficiency among EU countries. The Netherlands, Ireland, and Sweden demonstrate leading performance, while countries such as Bulgaria and Cyprus show considerable room for improvement. Overall, 20 out of 27 EU countries were found to be inefficient in implementing CE practices. A moderate positive correlation was also identified between CE efficiency and the level of countries' economic development.

Discussion: The results highlight the need for targeted policy interventions to enhance CE performance, particularly in lower-performing countries. The proposed DEA-based framework provides a valuable tool for benchmarking CE efficiency and informing evidence-based policymaking. By identifying leaders and laggards, the study contributes to understanding the territorial dynamics of the circular economy and supports the advancement of more effective and sustainable CE strategies.

KEYWORDS

circular economy, composite index, resource efficiency, data envelopment analysis, European Union, policy development

1 Introduction

The economic importance of securing access to resources is growing, and there is also growing concern over potential adverse social and environmental effects on third-world countries (Di Maio et al., 2017). Countries are becoming increasingly aware of the necessity to change existing practices, especially the ones related to the linear economy model, primarily due to the accumulation of an increasing number of problems including issues such as natural habitat loss, waste generated from unsustainable production and consumption, and their far-reaching implications for terrestrial and aquatic ecosystems

(Dzhengiz et al., 2023). Nevertheless, the economic development and preserving the natural environment's ability to regenerate are incompatible goals that have co-existed for some time (Du Plessis, 2012). The problems are particularly pronounced in urban areas and are related to the unsustainable use of land for urban expansion and the increasing vulnerability of certain settlements in recent decades (De Gregorio Hurtado, 2021) due to the unsustainable use of non-renewable resources and increased waste generation. Bonciu (2014) points out that limited resources and a small capacity for waste absorption are the limiting factors of the traditional linear economy.

The prevailing linear economic model, which is characterized by inefficient resource usage, is widely acknowledged as the fundamental cause of various contemporary environmental challenges, such as resource scarcity, unsustainable production and consumption patterns, habitat loss, pollution, and growing health concerns linked to mounting waste (Dzhengiz et al., 2023). The current multifaceted global challenge resulting from the combination of the COVID-19 pandemic, energy shortages, the ongoing war in Ukraine, and financial shocks caused by the bankruptcy of large banks has demonstrated the need to re-design the economy in a way to become proactive and not just reactive at a time of crisis. In the aftermath of the coronavirus pandemic it can be reckoned that prosperous, inclusive, low-carbon economy that reduces the likelihood of future crises will be necessary to achieve a recovery of the society (Ellen MacArthur Foundation, 2021a). Several approaches have been proposed in recent decades with the aim of solving the problem of the conventional linear economic model which is characterized by high volumes of resource inputs, high volumes of GDP outputs, and high volumes of pollutant emissions, such as the end-of-pipe treatment (Wu et al., 2014). However, the awareness of the unsustainability of the conventional linear economic model was amplified only recently, and academically and policy-wise more or less only after the introduction of the concept of the circular economy (Turner and Pearce, 1990).

Turner and Pearce (1990) applied the laws of thermodynamics to the circular economy, in the sense that in a closed system the overall energy remains constant, and therefore a zero balance amid consumed resources and released waste should be achieved (De Pascale et al., 2021). In this context, the circular economy appeared as a compromise solution that would help both the preservation of nature and the realization of economic progress offering a way to achieve sustainable development. Although, sustainability is commonly understood as a dynamic equilibrium between human activity and the ecosystem (Sonetti et al., 2019), newer perspective, the regenerative paradigm, emphasizes the creation of conditions that enable regenerative growth and enhance sustainability efficiency with the objective to achieve a positive balance in environmental and societal wellbeing through regenerative practices (Morseletto, 2020). Bearing that in mind, the circular economy represents a framework for resilience and regeneration that achieves numerous policy goals as a vital part of European agenda (Ellen MacArthur Foundation, 2021a). At the base of the circular economy is the concept of creating a regenerative economic system focused on optimizing the use of natural resources (Popović and Radivojević, 2022). Circular economy may be considered as a worldwide economic model based on design principles that aim to promote recovery and regeneration while ensuring maximum efficiency and value for products, components, and materials, while minimizing the use of limited resources (Liu et al., 2021). It is consider as a strategy to mitigate the impacts of linear practices, aiming to establish a restorative economic system that is less detrimental to the environment (de Oliveira and Oliveira, 2023).

Despite the widespread adoption of circular economy principles in policy frameworks, a critical question remains: how effectively are these principles implemented in practice? Therefore, the main goal of this research is to assess the efficiency of circular economy implementation across the European Union and find key factors influencing its success. The motivation for this research stems from the fact that despite the increasing emphasis on circular economy practices, there is still a gap in understanding how efficiently different EU countries implement these strategies. This study aims to bridge that gap by employing Data Envelopment Analysis (DEA) to evaluate and compare the circular economy performance of 27 EU countries. The key research question driving this study is: How efficiently do European Union countries implement circular economy principles, and what factors contribute to variations in their efficiency? By addressing this question, the study offers valuable insights that can inform policymakers and stakeholders in their efforts to enhance circular economy practices at the national and regional levels. The contributions of this research are threefold: (a) the development of a novel DEA-based composite indicator for circular economy efficiency, (b) an empirical evaluation of efficiency levels across EU countries, and (c) policy recommendations to improve circular economy performance based on best practices from leading countries.

The rest of the paper is structured as follows: the second section reviews the relevant literature, followed by the third section, which outlines the materials and methods; the fourth section presents an overview of the research results, which are then analyzed and discussed in the fifth section. Finally, the concluding remarks are provided in the last section.

2 Literature review

Academic discussions on the circular economy have emphasized its multidimensional nature, encompassing environmental, economic, and social dimensions. The circular economy framework has been increasingly integrated into policy agendas at both national and supranational levels, with circularity principles being embedded in the sustainability strategies of various entities. As the concept continues to evolve, scholars have looked to clarify its definition and scope. While there is no universally accepted definition of circular economy, several key contributions have tried to provide comprehensive explanations that summarize its essential characteristics and goals.

Morseletto (2020) defines circular economy as regenerative and restorative economy which encourages concepts such as regenerative agriculture, restorative environmental design, and regenerative development. Kirchherr et al. (2023) provided an extensive overview of 221 distinct definitions of the concept of the circular economy, proving the widespread interest in the topic and its evolving nature. Probably the most comprehensive definition of circular economy is proposed be (Su_arez-Eiroa et al., 2019) according to which circular economy represents a regenerative production and consumption system that strives to keep resource extraction and waste generation within safe limits for the planet by closing the system, minimizing its size, and maximizing the value of resources within the system. This is achieved primarily through effective design and education and can be implemented at any scale.

The circular economy is founded on three fundamental tenets (Morseletto, 2020): (a) cutting back on raw material intake and waste output, (b) preserving resources' value for as long as possible inside the system; and (c) reincorporating products back into the system once their life cycles are complete. Demestichas and Daskalakis (2020) provide further explanation about circular economy principles. Firstly, smarter product manufacturing is crucial, with an emphasis on energy and resource efficiency. By using sustainable materials and design principles, products can be created with minimal waste and pollution. Secondly, products and their components must be preserved for as long as possible, and their value optimized during subsequent lifecycles (Kristoffersen et al., 2021). This can be achieved through strategies such as redesign of products (Guldmann and Huulgaard, 2020), repair, refurbishment, and recycling. Finally, the circular economy model emphasizes the importance of regenerating virgin resources and restoring finite materials to be reused. By reusing and repurposing waste materials, valuable resources can be conserved, and pollution reduced.

The benefits of the circular economy for society are manifold. Firstly, circular economy should lead to waste reduction by prioritizing the reuse, refurbishment, and recycling of products and materials (López Ruiz et al., 2020) and ultimately help preserve natural resources, reduce pollution, and improve public health (Padilla-Rivera et al., 2020). Although 55% of greenhouse gas emissions can be tackled by energy efficiency and shifting to renewable energy sources, according to some studies the circular economy can help reduce the residual 45% of greenhouse gas emissions (Ellen MacArthur Foundation, 2021b). Furthermore, according to the Ellen MacArthur Foundation (2021b), the circular economy can play an important role in addressing the 90% of biodiversity loss and water stress caused by resource extraction and processing. On the other hand, staying on the path of a linear economy may cause severe consequences on the environment and worsen current global challenges. Therefore, the implementation of circular economy practices should have a positive impact on creating resilient communities, leading to improved wellbeing and quality of life. Secondly, the circular economy model encourages the resource efficiency which can help mitigate the environmental impact of economic activities and promote sustainable development (Korhonen et al., 2018). Thirdly, from an economic standpoint, the shift to a circular economy may create new job opportunities in sectors such as recycling, repair, and remanufacturing (Tambovceva et al., 2021), which should promote the development of more resilient and sustainable economies. Fourthly, the circular economy model requires new business models, products, and processes, which can foster innovation and creativity in industry and society (Bucea-Manea-ţoniş et al., 2021). Fifthly, by promoting more inclusive and equitable economic systems (Schröder et al., 2020), the circular economy can help address social and economic inequalities and create more justful communities. Moreover, for the equitable and sustainable future of human civilization it is especially important to address the problem of growing inequality with the same seriousness as environmental sustainability (Motesharrei et al., 2014). These potential benefits suggest that a transition to a circular economy can have multifold significant positive impacts on society, in terms of the environment and the economy, but also on social welfare and equity.

Nonetheless, when it comes to measuring progress towards circular economy, there is no single point of view among theorists and practitioners. In their study, Corona et al. (2019) systematically classified circularity metrics into two distinct categories. The first category encompasses circularity indices that are explicitly designed to assess the level of circularity within a given system. The second category consists of circularity assessment tools that are directed towards analyzing the influence of circular policies on the underlying tenets of the circular economy. This category can be further subdivided into two groups: (a) circular economy assessment indicators and (b) circular economy assessment frameworks (Stanković et al., 2021). These tools enable practitioners and researchers to evaluate the effectiveness of circular economy initiatives and policies, and to find areas for improvement in circularity practices. However, in addition these categories, there is also a difference in the level of the study, and consequently distinction among studies that cover level of (Pauliuk, 2018): (a) enterprise or products (micro-level); (b) industry (meso-level); and (c) city, region, or country (macro-level). Formerly, the largest span of the research was performed within micro (Cozzolino and De Giovanni, 2022; Ahmad et al., 2023; D'Angelo et al., 2023; Saccani et al., 2023; Shevchenko et al., 2023) and meso-level (Abbate et al., 2023; Salesa et al., 2023), but lately, there is also a number of macro-level research (Stanković et al., 2021; Bianchi et al., 2023; Reich et al., 2023). Nevertheless, it can be reckoned that a substantial volume of empirical research has emerged underscoring the necessity of transitioning from a linear model of consumption and production to a regenerative and circular system (Sarja et al., 2021; Rabiu and Jaeger-Erben, 2022).

Based on the review of the relevant literature, it can be concluded that circular economy has appeared as a key strategy for addressing challenges to sustainable development, and various metrics have been developed to assess the circularity of economic systems. In this context, this paper seeks to advance the field by proposing a novel approach to measuring circular economy development at the country level. Specifically, the paper draws on DEA which is a powerful technique for evaluating the efficiency of decision-making units, to construct a composite indicator of circular economy development. As the circular economy is a complex and multifaceted phenomenon, it is necessary to capture its various dimensions. So, this paper looks to provide a methodological framework for constructing a composite indicator that integrates multiple dimensions of circularity (e.g., resource efficiency, waste reduction, renewable energy use), enabling a comprehensive and comparative assessment of how effectively countries implement circular economy principles. The proposed approach builds on the principles of DEA, which is a non-parametric technique for measuring the efficiency of decision-making units based on multiple inputs and outputs. In the context of circular economy development, the inputs and outputs are defined in terms of the various dimensions of circularity, such as resource efficiency, waste reduction, and energy efficiency. By applying this approach to the data on the country-level, the paper aims to construct a composite indicator of circular economy development that can be used to benchmark and compare countries.

3 Materials and methods

Considering the increasing importance of circular economy in research, it is necessary to set up a framework for monitoring the implementation of circular economy practices. Even though indicators stand for essential tools in stakeholder decision-making, their effectiveness depends on the specific needs of the stakeholders and therefore they must be tailored to address those needs for stakeholders to be effective in decision-making. Gross domestic product is a commonly used indicator in the linear economy, however, it is less relevant in the context of the circular economy, highlighting the need to develop new indicators for monitoring circular strategies (Reich et al., 2023). For instance, the circular material use rate, measuring the share of recycled materials in overall material use, is a more suitable indicator for assessing progress toward circularity.

Starting in 2014, the European Commission has been actively endorsing the circular economy concept (European Commission, 2024) and has established a monitoring framework to oversee the advancement of circular economy implementation at both the country and European Union levels (European Commission, 2018). However, criticism has been leveled at current circularity metrics because they do not reflect the multifaceted and interdependent nature of the circular economy (Saidani et al., 2017). Specifically, though indicators are helpful in assessing the performance of countries towards specific targets, they do not provide the assessment of all aspects of circular economy which can lead to inaccurate estimations of performance (Giannakitsidou et al., 2020; de Oliveira and Oliveira, 2023).

The circular economy is a holistic concept that involves a range of interrelated dimensions, such as resource efficiency, waste reduction, and product design for reuse and recycling.

However, traditional circularity metrics often focus on a limited number of indicators and may not sufficiently reflect the interdependencies among these dimensions (Giannakitsidou et al., 2020). Moreover, circular economy performance also relates to broader outcomes, including economic competitiveness, innovation in business models, and job creation in green sectors (Korhonen et al., 2018; Tambovceva et al., 2021; Bucea-Manea-ţoniş et al., 2021). To address these complexities, composite indicators are increasingly used to provide a more integrated view by aggregating multiple relevant metrics into a single measure. This approach supports a more robust evaluation of circular economy performance and can better inform decision-makers and stakeholders at various levels.

When creating circular economy composite indicators, it is necessary to follow certain rules (Di Maio et al., 2017): (a) indicators and the decision-making process based on the indicators need to be comprehensible; (b) using a single aggregate indicator (composite indicator), instead of multiple indicators, simplifies communication and facilitates measuring progress towards agreed targets; (c) indicators must be robust and link to all relevant stakeholder issues at a specific place and time; and (d) indicators should rely on similar methodologies and harmonized statistics. Therefore, aggregation of singe indicators in the form of composite indicators may ease the understanding of the progress towards circular economy and serve as managerial and policy-making instrument (de Oliveira and Oliveira, 2023). Given the prominence of circular economy development for reaching sustainable development goals, it is critical to develop more robust and comprehensive metrics that better reflect the multidisciplinary and systemic nature of the circular economy. Such metrics can provide decision-makers with a more accurate and nuanced understanding of circular economy performance, allowing for more effective policy development and implementation. Henceforth, to measure the performance of European countries and create a composite indicator of circularity, the non-parametric method DEA was applied. Nevertheless, while composite indicators offer the advantage of summarizing complex, multidimensional phenomena into a single efficiency score, we acknowledge their limitations in capturing the full breadth of contextual and sector-specific nuances. As is the case with widely used indicators such as the Human Development Index, some degree of information loss is inevitable. However, in this study, the DEA-based composite indicator is used as a complementary tool that enables benchmarking and relative performance comparison, while still allowing for disaggregated analysis of individual inputs and outputs. This dual approach offers both a holistic perspective and the flexibility to 'zoom in' on specific dimensions of circular economy performance.

DEA is a widely used approach to evaluate the effectiveness of decision-making units in complex situations where multiple inputs and outputs are present. DEA relies on linear programming techniques to measure decision-making units' performance, and was first introduced in 1978 by Charnes, Cooper, and Rhodes (Charnes et al., 1978). In the linear programming model, weight coefficients are calculated to optimize the evaluation of the decision-making unit under analysis (Terzi and Pierini, 2015). One of the key advantages of DEA is that it does not require predetermined weight coefficients, which reduces the influence of the decision-maker and minimizes subjectivity. Instead, efficiency is determined by calculating the ratio of the weighted sum of outputs to the weighted sum of inputs. The DEA technique enables the identification of the most efficient decision-making units within a given set. Depending on the objective of the analysis, DEA models can be either output-oriented or input-oriented, with the former aiming to maximize outputs for a given input level, and the latter aiming to minimize inputs for a given output level (Al-Refaie et al., 2016; Stanković et al., 2020). Additionally, two different models can be identified based on the treatment of returns to scale: the CCR model with constant returns to scale (Charnes et al., 1978), and the BCC model with variable returns to scale (Banker and Charnes, 1984). The choice of model depends on the specific context and research question being addressed.

The modeling process assumes the presence of n decision-making units. Each unit produces s different outputs and uses m different inputs. To derive this efficiency score, the following linear programming model (Equations 1-5) is solved (Jemric and Vujcic, 2002):

TABLE 1 Definitions of input and output variables.

	Name	Definition
Inputs	Raw material consumption	The total amount of raw materials needed to produce the goods used by the economy
	Generation of municipal waste *per capita*	The quantity of waste produced by individuals in the form of domestic, commercial, and construction materials, which are gathered and processed by local authorities
	Greenhouse gas emissions intensity of energy consumption	The ratio between energy-related greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide) and gross inland energy consumption
Outputs	Recycling rate of municipal waste	The ratio of the weight of recycled municipal waste and the total weight of municipal waste generated
	Energy productivity	The ratio of GDP to total primary energy use (all the primary fuels and primary flows that a country uses to get energy)
	Share of energy from renewable sources	Percentage of energy obtained from renewable sources
	Resource productivity	The quantity of materials directly used by an economy (measured as domestic material consumption) in relation to GDP
	Circular material use rate	The ratio of the circular use of material to the total material use

Source: Authors' preview according to Eurostat (2024).

$$\max_{u} z_0 = \sum_{r=1}^{s} u_r y_{r0} \tag{1}$$

s.t.

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0, \; j = 1, 2 \ldots, n \tag{2}$$

$$\sum_{i=1}^{m} v_i x_{i0} = 1 \tag{3}$$

$$u_r \ge 0, r = 1, 2 \ldots s \tag{4}$$

$$v_i \ge 0, i = 1, 2 \ldots m \tag{5}$$

where u_r and v_i represent output and input weighting coefficients, respectively. The linear programming model's formulation yields the conclusion that a collection of weighting coefficients is endogenously ascertained to optimize their effectiveness within pre-determined constraints (Greco et al., 2019). Therefore, this approach enables a comprehensive assessment of each decision-making unit's performance relative to its peers, considering multiple inputs and outputs. Several studies also applied DEA when evaluating the circular economy efficiency mainly at meso or macro levels (Wu et al., 2014; Liu et al., 2019; Gastaldi et al., 2020; Giannakitsidou et al., 2020; Robaina et al., 2020; Wang et al., 2021; Halkos and Aslanidis, 2023) which indicates the validity of this technique for evaluating the performance of the European Unions' countries circular economy. By applying DEA method relative efficiency of decision-making units (countries) can be assessed by evaluating their inputs and outputs and may provide useful insights into the efficiency of circular economy practices. Measuring the efficiency of countries towards achieving a circular economy can be a complex task, as it involves assessing various indicators. To assess the efficiency of circular economy practices of the European Unions' countries, a model with eight indicators was developed. Indicators were obtained using the Eurostat database (Eurostat, 2024) for the year 2019 since it was the latest year with the data being available for all indicators (Table 1).

In this study, we employed a rigorous selection process to identify appropriate indicators for assessing the efficiency of circular economy practices across the European Union countries. Our approach was guided by established frameworks, particularly the European Commission's Circular Economy Monitoring Framework (Circular Economy, 2018) and the Competence Centre on Composite Indicators and Scoreboards (2022), to ensure that the selected indicators comprehensively reflect the multifaceted nature of circular economy. We adhered to the following criteria to ensure the robustness and relevance of our indicators (Competence Centre on Composite Indicators and Scoreboards, 2022): a indicators were selected based on their alignment with key circular economy strategies, such as resource efficiency and waste reduction; (b) indicators for which consistent and reliable data are available across all 27 EU countries were prioritized; (c) selected indicators are quantifiable, allowing for objective assessment and analysis; (d) indicators were chosen based on their significance to current EU policies and targets related to sustainable development and circular economy practices. The selected indicators collectively provide a comprehensive overview of circular economy performance by capturing various dimensions of circularity. This multifaceted approach aligns with the European Academies Science Advisory Council's recommendation to utilize a diverse set of indicators to effectively monitor circular economy progress (EASAC, 2016). Descriptive statistics of the selected indicators are provided in Table 2.

4 Results

To obtain circular economy efficiency scores for the European Union countries the Charnes, Cooper, and Rhodes (CCR) specification of the input-oriented DEA model was implemented. This model was chosen due to its ability to measure the relative efficiency of decision-making units by comparing their input-output relationships, making it particularly suitable for assessing the effectiveness of circular economy strategies. The DEA analysis was conducted using Efficiency Measurement System (EMS) software, which is widely used for efficiency measurement and benchmarking (Scheel, 2000). The input-oriented DEA model was implemented to evaluate how efficiently each country utilizes

TABLE 2 Descriptive statistics.

Indicator	Unit of measurement	Minimum	Maximum	Mean	Std. Deviation	Variance
Raw material consumption	Tonnes	7.67	32.55	18.44	6.38	40.77
Generation of municipal waste *per capita*	Kilograms *per capita* per year	280.00	844.00	514.93	129.20	16691.61
Greenhouse gas emissions intensity of energy consumption	Index (2000 = 100)	58.90	102.60	81.77	10.07	101.44
Recycling rate of municipal waste	Percentage of total municipal waste	9.10	66.70	39.60	14.57	212.37
Energy productivity	Euros per kilogram of oil equivalent	2.45	19.40	7.52	3.70	13.72
Share of energy from renewable sources	Percentage of total energy consumption	7.05	55.79	22.43	11.92	142.03
Resource productivity	Euro per kilogram of material consumption	0.36	4.97	1.87	1.17	1.37
Circular material use rate	Percentage of total material use	1.30	30.00	9.47	7.10	50.43

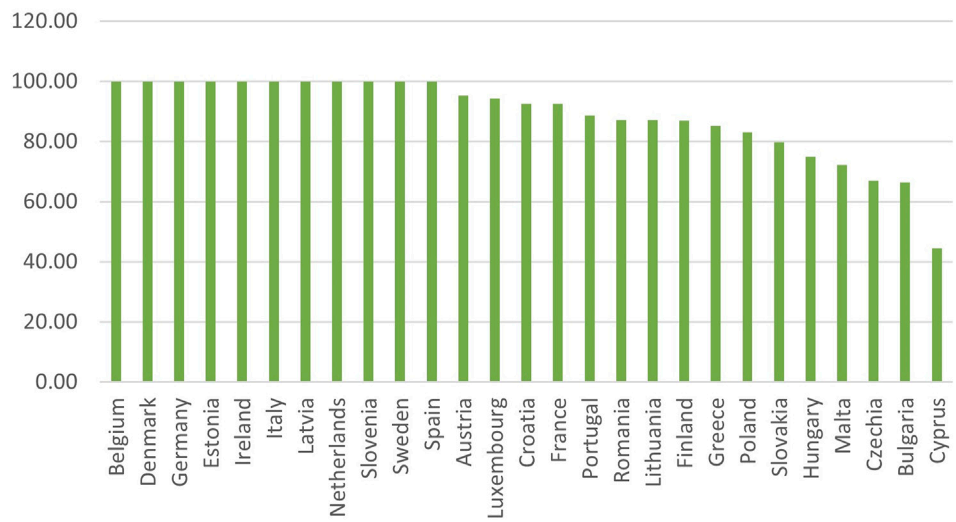

FIGURE 1
Results of the CCR model obtained using EMS software.

its available resources (inputs) to achieve desired circular economy outcomes (outputs). The input-oriented approach was selected because circular economy strategies primarily focus on minimizing resource use and optimizing sustainability-related processes, making it essential to assess efficiency from an input minimization perspective. The selected indicators, reflecting both resource utilization and circular economy outcomes, were carefully chosen based on their relevance, accessibility, and representativeness, ensuring that the analysis provides meaningful insights into the territorial efficiency of circular economy implementation.

Figure 1 presents the results of the CCR model, displaying the circular economy efficiency scores. The y-axis represents the efficiency levels of European Union countries, while the x-axis lists the analyzed EU member states. The results show that the worst relative performers with respect to the obtained composite indicator are Cyprus, Bulgaria, Czech Republic, and Malta, while almost the half of the analyzed countries (11 countries) are among efficient countries regarding their circular economy performance.

It can be observed that, when employing the conventional DEA model for assessing the efficiency of decision-making units, it is plausible that the efficiency metrics of multiple decision-making units may concurrently be equivalent to one (one), thereby impeding further comparison and analysis of efficient decision-making units. Therefore, to obtain the ranking of decision-making units (countries) it is favorable to implement Super-Efficiency DEA (Andersen and Petersen, 1993). According to the Super-Efficiency DEA model efficient decision-making units may have efficiency scores greater than one. On the other hand, the super efficiency score of an inefficient decision-making unit is identical to its efficiency score in the CCR model. Furthermore, in an input-oriented DEA model, the higher value of super efficiency score indicates an increasing level of efficiency, while for inefficient decision-making units' lower super efficiency score shows a decreasing level of

TABLE 3 Values of super-efficiency composite indices and ranking of countries.

Country	Super-efficiency CI
Netherlands	219.25
Ireland	163.22
Sweden	159.70
Denmark	139.79
Estonia	117.73
Belgium	115.80
Germany	115.18
Latvia	111.50
Italy	109.51
Slovenia	100.75
Spain	99.84
Austria	95.26
Luxembourg	94.23
Croatia	92.58
France	92.54
Portugal	88.65
Romania	87.15
Lithuania	87.05
Finland	86.86
Greece	85.14
Poland	83.03
Slovakia	79.80
Hungary	74.94
Malta	72.28
Czech Republic	66.92
Bulgaria	66.44
Cyprus	44.56
Average value	101.84

efficiency. Regarding the super-efficiency scores, the results indicate that at the level of the European Union average circular economy efficiency is greater than one (one), indicating an upward trend regarding the circular economy performance (Table 3).

However, when it comes to the country level, heterogeneity of efficiency scores may be observed (Figure 2) with the Netherlands, Ireland, and Sweden, being the most efficient countries.

To examine whether circular economy performance is related to the level of economic development of a country, a correlation analysis is performed, and the results reveal that there is a moderate, positive correlation between circular economy efficiency and GDP *per capita* (value of Spearman's correlation coefficient is 0.536). This points to the fact that there is potentially a link between the level of the countries' wealth and progress towards a circular economy, since the implementation of circular economy principles requires significant investment and expenditure related to the adoption of sophisticated technology, continuous knowledge creation and advanced infrastructure development that may not be feasible for less developed countries. This suggests that economically disadvantaged nations need customized support measures aimed at modernizing their economies and enhancing the efficiency of their production factors (Nazarko et al., 2022).

5 Discussion

The circular economy concept is viewed as a potential resolution to reconcile aspirations for economic expansion and environmental preservation, as it seeks to eliminate waste in the production and consumption of goods (Ghisellini et al., 2016). Advocates of the circular economy emphasize that closing material loops has the potential to transform our existing linear model of production and consumption, which is presently deemed unsustainable due to the limited supply of non-renewable resources, as well as the increasing and more prosperous global population (Bianchi and Cordella, 2023). Accordingly, the circular economy strives to safeguard the natural resources of the environment by minimizing waste generation and energy consumption (Bianchi et al., 2023). Furthermore, it presents opportunities to stimulate local economies by generating new job prospects that prioritize circular-oriented activities, and by generating markets for secondary raw materials (Ghisellini et al., 2016).

When it comes to the analysis conducted, the results show that more than 40% of the countries analyzed are efficient in terms of circular economy development. On the other hand, more than a half of the European Union's countries are inefficient, although on average the level of efficiency is higher than one (one). The obtained efficiency scores show that these countries are below the circular economy production frontier and a lot more needs to be done to establish a way towards achieving the circular economy targets. The varying pace at which EU member states adopt circular economy models can be attributed to several factors, including differences in infrastructure and public acceptance of legislative measures (Castillo-Díaz et al., 2024). While all member states are required to adhere to common EU regulations, national commitment to sustainability and the circular economy significantly influences implementation. For example, countries some countries proactively established circular economy policies prior to the EU's overarching strategy, whereas others have yet to develop specific national strategies (Škrinjarí, 2020).

Nevertheless, if the efficient countries are analyzed further, it can be determined that, based on the analyzed indicators, the Netherlands is currently the leader in the development of the circular economy in the European Union (Table 2). These findings align with previous research indicating that the Netherlands consistently rank at the top in circular economy performance, while Mediterranean nations often lag behind (Mazur-Wierzbicka, 2021; Stanković et al., 2021; Ūsas et al., 2021; Nazarko et al., 2022; Marković et al., 2023; Martínez Moreno et al., 2023; Castillo-Díaz et al., 2024; D'Adamo et al.,

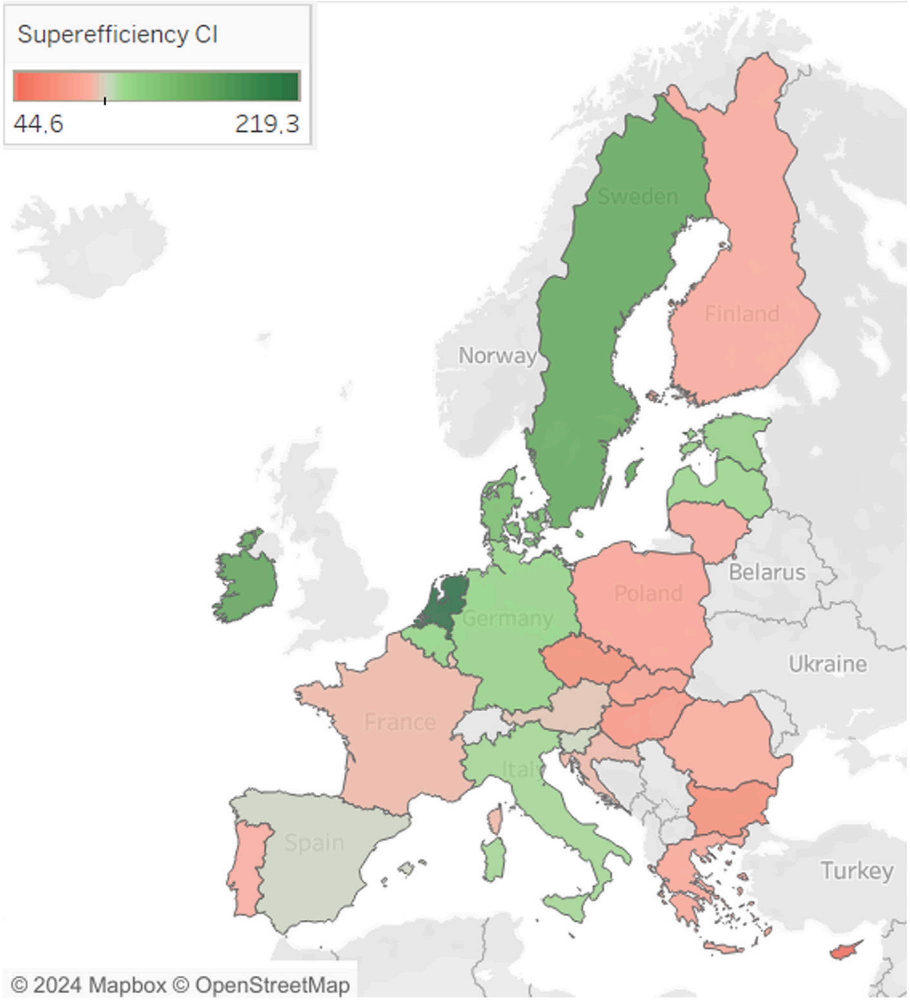

FIGURE 2
Graphical representation of the super-efficiency composite index (CI) results using Tableau Desktop Public Edition 2024.2.2.

2024). Netherlands is a leader in circular economy initiatives, aiming for full circularity by 2050 (Cramer, 2022). As of 2023, the country's circular material use rate stands at 30.6%, the highest in Europe (European Environment Agency, 2024). There are several reasons for the Netherlands being the country with the best performance concerning circular economy (Circular Economy, 2016): (a) the Netherlands has established a long-term vision and comprehensive policy framework to achieve a circular economy; (b) the Netherlands has a highly developed waste management system that includes advanced sorting technologies and a well-established recycling infrastructure with one of the highest recycling rates in Europe (over 80% of waste is being recycled or reused); (c) the Netherlands has a strong culture of collaboration between businesses, governments, and civil society which has led to the development of innovative business models and circular supply chains that aim to reduce waste and maximize the value of resources; (d) the Netherlands has invested heavily in research and development, which has resulted in the development of new technologies and innovations that support circular practices; (e) the Netherlands has a highly educated workforce that is well-equipped to implement circular practices.

On the other hand, countries at the bottom of the list are still in the first stages of transitioning towards a circular economy. While these countries have taken steps towards reducing waste and promoting sustainable practices, they still face challenges in implementing circular economy policies. On their road towards achieving circular economy efficiency, it is necessary to draw lessons from the experiences of countries with a developed circular economy. Škrinjarí (2020) suggests that to advance circular economy and sustainable development goals, it is essential to implement robust monitoring mechanisms to assess progress, enhance public awareness to drive governmental and industrial accountability, reduce reliance on imported raw materials through recycling initiatives, leverage European Union funds for job creation and infrastructure modernization, and reform tax policies to incentivize sustainable practices. Recommendations for inefficient countries towards achieving circular efficiency include the necessity of strategic focus and the creation of a comprehensive circular economy strategy, encouraging cooperation between different sectors, promoting innovation and entrepreneurship, investing in infrastructure, and raising citizens' awareness of the importance of the circular economy for the achievement of sustainable development. D'Adamo et al. (2024) argue that both companies and citizens must play an integral role in driving change, which can be achieved by addressing the following challenges: (a) reducing illegal waste, (b) increasing investment in circular technologies, and (c) ensuring a more equitable distribution of the benefits derived from circular models across various stakeholder groups.

While the circular economy model has many potential benefits, there are also some challenges and disadvantages that should be considered. The transition to circular economy can be complex and difficult, particularly for traditional linear business models. Adopting circular economy practices requires significant changes in the way businesses operate, which can be challenging and costly. Additionally, many circular economy practices, such as recycling and remanufacturing, require significant investment in new technologies, equipment, and processes which can represent an entry barrier for some businesses and industries. Furthermore, some circular economy practices are technically challenging and may require specialized expertise and equipment. Consumer behaviors also may represent challenge for the implementation of circular economy practices since changing consumer behavior can be difficult, particularly if there is a perception that reused or refurbished products are of lower quality than new ones. These potential disadvantages suggest that the full transition of European Unions' countries to circular economy will not be easy or straightforward, and that there may be some significant challenges that need to be addressed to fully realize the benefits of this model.

6 Conclusion

The concept of circular economy has appeared as a promising alternative to the traditional linear economy model. The linear model, which depends on the constant extraction of virgin and non-renewable resources, manufacturing of products, and disposal of waste after their first lifecycle, has led to significant environmental degradation and depletion of resources. In contrast, the circular economy model purposes to create a closed-loop system where resources are used efficiently, waste and pollution are minimized, and materials and products are retained at their highest value for as long as possible. By embracing regenerative development and circularity, individuals, businesses, and governments can create a more sustainable and resilient economic system that is better equipped to withstand future crises and shocks. Moreover, these approaches can also contribute to creating a fairer and more prosperous society, while preserving natural resources for future generations.

The assessment of circular economy efficiency across European Union countries can yield substantial benefits for policymakers. By drawing on the principles of DEA, the paper offered methodological framework for constructing a composite indicator of circular economy development. This approach has the potential to help evidence-based decision-making and policy development aimed at promoting circularity and sustainable development. The transition towards circular economy requires effective policy design, coordination, and interoperability among various stakeholders from different sectors. This is especially critical considering that more countries are developing roadmaps for the circular economy and incorporating this concept into their green recovery initiatives. Collaboration between various actors is essential for achieving a circular economy, and policy can serve as a key driver in promoting this transition. Policymakers must therefore take the lead in creating a conducive environment and removing potential barriers that may impede the shift towards a circular economy. With effective policy implementation, a circular economy can become a reality, leading to improved economic, social, and environmental outcomes. Therefore, the resulting ranking of European Union member states can serve as a valuable tool for identifying efficient countries and learning from their best practices to improve the circular economy performance of the inefficient ones.

By using this approach, decision-makers can gain insights into the most efficient use of resources, provide adequate strategic planning, and improve overall performance. Nevertheless, it should be mentioned that these metrics are meant to supplement rather than replace the conventional single indicators, providing a more thorough understanding of the performance of the countries (Giannakitsidou et al., 2020). The conducted study faces with several limitations: (a) the efficiency results are influenced by the choice of variables; (b) obtaining valid results requires compliance with the rules related to the relationship between the sample size and the number of indicators (input and output variables) included in the model, whereby the rule is that the number of decision-making units is at least three times greater than the number of indicators, which limits the maximum number of indicators that could be used to eight; (c) the obtained results are static by nature and are related to a specific year, so it is not possible to follow the dynamics of the development of the circular economy over time. Nevertheless, the results obtained give a picture of the state of development of the circular economy in the countries of the European Union and provide sufficient information based on which it is possible to find the best practices and to create guidelines for decision-making. Further research can be directed towards including other time periods, after more recent data becomes available, and to perform a comparative analysis of the results, as well as checking the dynamics of efficiency over time.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://ec.europa.eu/eurostat/web/circular-economy/database.

Author contributions

IM: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review and editing. JS: Conceptualization, Funding acquisition, Supervision, Validation, Writing – original draft. JÖ: Conceptualization, Validation, Writing – original draft. MM: Data curation, Methodology, Writing – original draft, Writing – review and editing. MS: Visualization, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abbate, S., Centobelli, P., Cerchione, R., Giardino, G., and Passaro, R. (2023). Coming out the egg: assessing the benefits of circular economy strategies in agri-food industry. *J. Clean. Prod.* 385 (2), 135665. doi:10.1016/j.jclepro.2022.135665

Ahmad, F., Bask, A., Laari, S., and Robinson, C. V. (2023). Business management perspectives on the circular economy: present state and future directions. *Technol. Forecast. Soc. Change* 187 (2), 122182. doi:10.1016/j.techfore.2022.122182

Al-Refaie, A., Hammad, M., and Li, M. H. (2016). DEA window analysis and Malmquist index to assess energy efficiency and productivity in Jordanian industrial sector. *Energy Effic.* 9 (6), 1299–1313. doi:10.1007/s12053-016-9424-0

Andersen, P., and Petersen, N. C. (1993). A procedure for ranking efficient units in data envelopment analysis. *Manag. Sci.* 39 (10), 1261–1264. doi:10.1287/mnsc.39.10.1261

Banker, R. D., Charnes, A. and W. C. W., and Cooper, W. W. (1984). Some models for estimating technical and scale inefficiencies in data envelopment analysis. *Manag. Sci.* 30 (9), 1078–1092. doi:10.1287/mnsc.30.9.1078

Bianchi, M., and Cordella, M. (2023). Does circular economy mitigate the extraction of natural resources? Empirical evidence based on analysis of 28 European economies over the past decade. *Ecol. Econ.* 203 (September 2022), 107607. doi:10.1016/j.ecolecon.2022.107607

Bianchi, M., Cordella, M., and Menger, P. (2023). Regional monitoring frameworks for the circular economy: implications from a territorial perspective. *Eur. Plan. Stud.* 31 (1), 36–54. doi:10.1080/09654313.2022.2057185

Bonciu, F. (2014). The European economy: from a linear to a circular economy. *Romanian J. Eur. Aff.* 14 (4), 78–91.

Bucea-Manea-ţoniş, R., Šević, A., Ilić, M. P., Bucea-Manea-Ţoniş, R., Popović Šević, N., and Mihoreanu, L. (2021). Untapped aspects of innovation and competition within a european resilient circular economy. A dual comparative study. *Sustain. Switz.* 13 (15), 8290. doi:10.3390/su13158290

Castillo-Díaz, F. J., Belmonte-Ureña, L. J., Diánez-Martínez, F., and Camacho-Ferre, F. (2024). Challenges and perspectives of the circular economy in the European Union: a comparative analysis of the member states. *Ecol. Econ.* 224 (June), 108294. doi:10.1016/j.ecolecon.2024.108294

Charnes, A., Cooper, W. W., and Rhodes, E. (1978). Measuring the efficiency of decision making units. *Eur. J. Operational Res.* 2 (6), 429–444. doi:10.1016/0377-2217(78)90138-8

Circular Economy (2016). A circular economy in The Netherlands by 2050. Available online at: https://circulareconomy.europa.eu/platform/sites/default/files/17037circulaireeconomie_en.pdf (Accessed on June 24, 2024).

Circular Economy (2018). Circular economy monitoring framework. Available online at: https://ec.europa.eu/eurostat/web/circular-economy/monitoring-framework (Accessed on March 22, 2025).

Competence Centre on Composite Indicators and Scoreboards (2022). Step 2. Data selection. Available online at: https://knowledge4policy.ec.europa.eu/composite-indicators/10-step-guide/step-2-data-selection_en (Accessed on June 12, 2024).

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., and Worrell, E. (2019). Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. *Resour. Conservation Recycl.* 151 (September 2019), 104498. doi:10.1016/j.resconrec.2019.104498

Cozzolino, A., and De Giovanni, P. (2022). Portfolios of sustainable practices for packaging in the circular economy: an analysis of Italian firms. *Int. J. Logist. Manag.* 34 (7), 24–49. doi:10.1108/IJLM-03-2022-0132

Cramer, J. (2022). Effective governance of circular economies: an international comparison. *J. Clean. Prod.* 343, 130874. doi:10.1016/j.jclepro.2022.130874

D'Adamo, I., Favari, D., Gastaldi, M., and Kirchherr, J. (2024). Towards circular economy indicators: evidence from the European Union. *Waste Manag. Res.* 42, 670–680. doi:10.1177/0734242X241237171

D'Angelo, V., Cappa, F., and Peruffo, E. (2023). Walking the tightrope: circular economy breadth and firm economic performance. *Corp. Soc. Responsib. Environ. Manag.* 30 (4), 1869–1882. doi:10.1002/csr.2460

De Gregorio Hurtado, S. (2021). "Adaptation to climate change as a key dimension of urban regeneration in Europe: the cases of Copenhagen, Vienna, and Madrid," in *Rethinking sustainability towards a regenerative economy* (Cham: Springer International Publishing), 65–89.

Demestichas, K., and Daskalakis, E. (2020). Information and communication technology solutions for the circular economy. *Sustain. Switz.* 12 (18), 7272–7319. doi:10.3390/su12187272

de Oliveira, C. T., and Oliveira, G. G. A. (2023). What Circular economy indicators really measure? An overview of circular economy principles and sustainable development goals. *Resour. Conservation Recycl.* 190 (September 2022), 106850. doi:10.1016/j.resconrec.2022.106850

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., and Ioppolo, G. (2021). A systematic review for measuring circular economy: the 61 indicators. *J. Clean. Prod.* 281, 124942. doi:10.1016/j.jclepro.2020.124942

Di Maio, F., Rem, P. C., Baldé, K., and Polder, M. (2017). Measuring resource efficiency and circular economy: a market value approach. *Resour. Conservation Recycl.* 122, 163–171. doi:10.1016/j.resconrec.2017.02.009

Du Plessis, C. (2012). Towards a regenerative paradigm for the built environment. *Build. Res. Inf.* 40 (1), 7–22. doi:10.1080/09613218.2012.628548

Dzhengiz, T., Miller, E. M., Ovaska, J., and Patala, S. (2023). Unpacking the circular economy: a problematizing review. *Int. J. Manag. Rev.* 25, 270–296. doi:10.1111/ijmr.12329

EASAC (2016). Indicators for a circular economy - European Academies science advisory Council. Available online at: https://easac.eu/fileadmin/PDF_s/reports_statements/Circular_Economy/EASAC_Indicators_web_complete.pdf (Accessed on July 7, 2024).

Ellen MacArthur Foundation (2021a). How policymakers can pave the way to a low-carbon and prosperous future. Available online at: https://ellenmacarthurfoundation.org/covid-policymakers (Accessed on July 5, 2024).

Ellen MacArthur Foundation (2021b). *Universal circular economy policy goals'*. Isle of Wight, United Kingdom Ellen MacArthur Foundation. Available online at: https://www.ellenmacarthurfoundation.org/universal-policy-goals/overview (Accessed on July 5, 2024).

European Commission (2018). A monitoring framework for the circular economy. *Strasbourg* 29, 1–11. Available online at: https://commission.europa.eu/publications/monitoring-framework-circular-economy_en (Accessed on June 15, 2024).

European Commission (2024). First circular economy action plan. Available online at: https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en (Accessed on June 11, 2024).

European Environment Agency (2024). Circular material use rate in Europe. Available online at: https://www.eea.europa.eu/en/analysis/indicators/circular-material-use-rate-in-europe (Accessed on June 8, 2024).

Eurostat (2024). Circular economy database. Available online at: https://ec.europa.eu/eurostat/web/circular-economy/database (Accessed on May 30, 2024).

Gastaldi, M., Lombardi, G. V., Rapposelli, A., and Romano, G. (2020). 'The efficiency of waste sector in Italy: an application by data envelopment analysis', 24(3) 225–238. doi:10.2478/rtuect-2020-0099

Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114, 11–32. doi:10.1016/j.jclepro.2015.09.007

Giannakitsidou, O., Giannikos, I., and Chondrou, A. (2020). Ranking European countries on the basis of their environmental and circular economy performance: a DEA application in MSW. *Waste Manag.* 109, 181–191. doi:10.1016/j.wasman.2020.04.055

Greco, S., Ishizaka, A., Tasiou, M., and Torrisi, G. (2019). On the methodological framework of composite indices: a review of the issues of weighting, aggregation, and robustness. *Soc. Indic. Res.* 141, 61–94. doi:10.1007/s11205-017-1832-9

Guldmann, E., and Huulgaard, R. D. (2020). Barriers to circular business model innovation: a multiple-case study. *J. Clean. Prod.* 243, 118160. doi:10.1016/j.jclepro.2019.118160

Halkos, G. E., and Aslanidis, P. S. C. (2023). New circular economy perspectives on measuring sustainable waste management productivity. *Econ. Analysis Policy* 77, 764–779. doi:10.1016/j.eap.2023.01.001

Jemric, I., and Vujcic, B. (2002). Efficiency of banks in Croatia: a DEA approach. *Comp. Econ. Stud.* 44 (2–3), 169–193. doi:10.1057/ces.2002.13

Kirchherr, J., Yang, N. H. N., Schulze-Spüntrup, F., Heerink, M. J., and Hartley, K. (2023). Conceptualizing the circular economy (revisited): an analysis of 221 definitions. *Resour. Conservation Recycl.* 194 (April), 107001. doi:10.1016/j.resconrec.2023.107001

Korhonen, J., Honkasalo, A., and Seppälä, J. (2018). Circular economy: the concept and its limitations. *Ecol. Econ.* 143, 37–46. doi:10.1016/j.ecolecon.2017.06.041

Kristoffersen, E., Mikalef, P., Blomsma, F., and Li, J. (2021). The effects of business analytics capability on circular economy implementation, resource orchestration capability, and firm performance. *Int. J. Prod. Econ.* 239 (April), 108205. doi:10.1016/j.ijpe.2021.108205

Liu, X., Guo, P., and Guo, S. (2019). Assessing the eco-efficiency of a circular economy system in China's coal mining areas: emergy and data envelopment analysis. *J. Clean. Prod.* 206, 1101–1109. doi:10.1016/j.jclepro.2018.09.218

Liu, Z., Liu, J., and Osmani, M. (2021). Integration of digital economy and circular economy: current status and future directions. *Sustain. Switz.* 13 (13), 7217. doi:10.3390/su13137217

López Ruiz, L. A., Roca Ramón, X., and Gassó Domingo, S. (2020). The circular economy in the construction and demolition waste sector – a review and an integrative model approach. *J. Clean. Prod.* 248, 119238. doi:10.1016/j.jclepro.2019.119238

Marković, M., Popović, Z., and Marjanović, I. (2023). Towards a circular economy: evaluation of waste management performance in European union countries. *Serbian J. Manag.* 18 (1), 45–57. doi:10.5937/sjm18-40073

Martínez Moreno, M. M., Buitrago Esquinas, E. M., Yñiguez, R., and Puig-Cabrera, M. (2023). A global and comparative assessment of the level of economic circularity in the EU. *J. Clean. Prod.* 425 (August 2023), 138759. doi:10.1016/j.jclepro.2023.138759

Mazur-Wierzbicka, E. (2021). Towards circular economy—a comparative analysis of the countries of the European Union. *Resources* 10 (5), 49. doi:10.3390/resources10050049

Morseletto, P. (2020). Restorative and regenerative: exploring the concepts in the circular economy. *J. Industrial Ecol.* 24 (4), 763–773. doi:10.1111/jiec.12987

Motesharrei, S., Rivas, J., and Kalnay, E. (2014). Human and nature dynamics (HANDY): modeling inequality and use of resources in the collapse or sustainability of societies. *Ecol. Econ.* 101, 90–102. doi:10.1016/j.ecolecon.2014.02.014

Nazarko, J., Chodakowska, E., and Nazarko, Ł. (2022). Evaluating the transition of the European union member states towards a circular economy. *Energies* 15 (11), 3924. doi:10.3390/en15113924

Padilla-Rivera, A., Russo-Garrido, S., and Merveille, N. (2020). Addressing the social aspects of a circular economy: a systematic literature review. *Sustain. Switz.* 12 (19), 7912–7917. doi:10.3390/SU12197912

Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001: 2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resour. Conservation Recycl.* 129, 81–92. doi:10.1016/j.resconrec.2017.10.019

Popović, A., and Radivojević, V. (2022). The circular economy: principles, strategies and goals. *Econ. Sustain. Dev.* 6 (1), 45–56. doi:10.5937/esd2201045p

Rabiu, M. K., and Jaeger-Erben, M. (2022). Appropriation and routinisation of circular consumer practices: a review of current knowledge in the circular economy literature. *Clean. Responsible Consum.* 7 (September 2021), 100081. doi:10.1016/j.clrc.2022.100081

Reich, R. H., Vermeyen, V., Alaerts, L., and Van Acker, K. (2023). How to measure a circular economy: a holistic method compiling policy monitors. *Resour. Conservation Recycl.* 188 (October 2022), 106707. doi:10.1016/j.resconrec.2022.106707

Robaina, M., Murillo, K., Rocha, E., and Villar, J. (2020). Circular economy in plastic waste - efficiency analysis of European countries. *Sci. Total Environ.* 730, 139038. doi:10.1016/j.scitotenv.2020.139038

Saccani, N., Bressanelli, G., and Visintin, F. (2023). Circular supply chain orchestration to overcome Circular Economy challenges: an empirical investigation in the textile and fashion industries. *Sustain. Prod. Consum.* 35, 469–482. doi:10.1016/j.spc.2022.11.020

Saidani, M., Yannou, B., Leroy, Y., and Cluzel, F. (2017). How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. *Recycling* 2, 6. doi:10.3390/recycling2010006

Salesa, A., León, R., and Moneva, J. M. (2023). Airlines practices to incorporate circular economy principles into the waste management system. *Corp. Soc. Responsib. Environ. Manag.* 30 (1), 443–458. doi:10.1002/csr.2365

Sarja, M., Onkila, T., and Mäkelä, M. (2021). A systematic literature review of the transition to the circular economy in business organizations: obstacles, catalysts and ambivalences. *J. Clean. Prod.* 286, 125492. doi:10.1016/j.jclepro.2020.125492

Scheel, H. (2000). Efficiency measurement system, EMS: efficiency measurement system user's manual. Available online at: https://www.holger-scheel.de/ems/.

Schröder, P., Lemille, A., and Desmond, P. (2020). Making the circular economy work for human development. *Resour. Conservation Recycl.* 156 (September 2019), 104686. doi:10.1016/j.resconrec.2020.104686

Shevchenko, T., Saidani, M., Ranjbari, M., Kronenberg, J., Danko, Y., and Laitala, K. (2023). Consumer behavior in the circular economy: developing a product-centric framework. *J. Clean. Prod.* 384 (December 2022), 135568. doi:10.1016/j.jclepro.2022.135568

Škrinjarí, T. (2020). Empirical assessment of the circular economy of selected European countries. *J. Clean. Prod.* 255, 120246. doi:10.1016/j.jclepro.2020.120246

Sonetti, G., Brown, M., and Naboni, E. (2019). About the triggering of UN sustainable development goals and regenerative sustainability in higher education. *Sustain. Switz.* 11 (1), 254. doi:10.3390/su11010254

Stanković, J., Janković-Milić, V., Marjanović, I., and Janjić, J. (2021). An integrated approach of PCA and PROMETHEE in spatial assessment of circular economy indicators. *Waste Manag.* 128, 154–166. doi:10.1016/j.wasman.2021.04.057

Stanković, J. J., Marjanović, I., and Stojković, N. (2020). DEA assessment of socio-economic development of European countries. *Management:Journal Sustain. Bus. Manag. Solutions Emerg. Econ.*, 1–11. doi:10.7595/management.fon.2020.0012

Su_arez-Eiroa, B. (2019). Operational principles of circular economy for sustainable development. *Link. theory Pract.* 214, 952–961. doi:10.1016/j.jclepro.2018.12.271

Tambovceva, T. T., Melnyk, L. H., Dehtyarova, I. B., and Nikolaev, S. O. (2021). Circular economy: tendencies and development perspectives. *Mech. Econ. Regul.* 2021 (2), 33–42. doi:10.21272/mer.2021.92.04

Terzi, S., and Pierini, A. (2015). Data Envelopment Analysis (DEA) assessment of composite indicators of infrastructure endowment. *Riv. Stat. Uff.* 1, 5–18. Available online at: http://www.istat.it/it/files/2015/05/Art.1-Data-envelopment.analysis-infrastructure-endowment.pdf.

Turner, R. K., and Pearce, D. W. (1990). *The ethical foundations of sustainable economic development*. London: International Institute for Environment and Development.

Ūsas, J., Balezentis, T., and Streimikiene, D. (2021). Development and integrated assessment of the circular economy in the European Union: the outranking approach. *J. Enterp. Inf. Manag.* 38 (1), 243–260. doi:10.1108/JEIM-11-2020-0440

Wang, S., Lei, L., and Xing, L. (2021). Urban circular economy performance evaluation: a novel fully fuzzy data envelopment analysis with large datasets. *J. Clean. Prod.* 324 (January), 129214. doi:10.1016/j.jclepro.2021.129214

Wu, H. Q., Shi, Y., Xia, Q., and Zhu, W. d. (2014). Effectiveness of the policy of circular economy in China: a DEA-based analysis for the period of 11th five-year-plan. *Resour. Conservation Recycl.* 83, 163–175. doi:10.1016/j.resconrec.2013.10.003