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Managing waste packaging for a sustainable future: a strategic and efficiency analysis in the European context

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Abstract

The management of package waste has become a critical concern in pursuing sustainable development, particularly within the European context, where environmental regulations and sustainability goals are stringent. This paper presents a comprehensive strategic and efficiency analysis of waste packaging management across Europe, examining current practices, policies, and technological innovations in a sample of countries. The work identifies critical challenges and opportunities in the sector using Data Envelopment Analysis and Multicriteria decision analysis. Our findings reveal significant variations in the efficiency and effectiveness of waste packaging management practices among European countries, influenced by differing policy frameworks, recycling infrastructures, and public awareness levels. Sweden and Luxembourg excel in the sustainable and technical model for recycling, while Austria prevails for recovery in both. The strategic vision suggests an emphasis on green premium, and the most sustainable alternatives are those marked by natural fibres and respect for human conditions. The paper concludes with strategic recommendations for policymakers, industry stakeholders, and communities to enhance waste packaging management efficiency. These include policy harmonisation at the EU level, investment in innovative recycling technologies, and fostering public–private partnerships to drive systemic change. By adopting these strategies, Europe can move closer to achieving its sustainability targets, reducing environmental impact, and promoting a circular economy. So, the implications of this paper are both strategic and political. The former is related to identifying the best strategy related to packaging waste, and the latter is to uniform the efficiency of waste packaging management in Europe.

Keywords Efficiency analysis · Europe · Strategic analysis · Sustainable development · Waste packaging

1 Introduction

The Sustainable Development Goals (SDGs) play a crucial role in identifying pragmatic models that identify solutions to current problems to counter climate change (D'Adamo et al., 2024b), and these challenges require the contribution of universities (Leal Filho et al., 2023, 2024c). The context of reference concerns some significant challenges involving

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the water-energy-food model within SDG (D'Amore et al., 2022), Multi-stakeholder partnerships as a critical enabler for SDG implementation (Eweje et al., 2021), relationships between circular economy and waste within accountability models (Di Vaio et al., 2023), digital waste disposal processes through the sharing of programs to define waste disposal practices (Di Vaio et al., 2024a), renewable energy sources to decarbonize waste disposal practices (Di Vaio et al., 2024b) and responsible business strategy based on knowledge sharing (Di Vaio et al., 2022; Zhong et al., 2024). The topic of circular economy (CE) is essential to supporting the competitiveness of companies and directing their strategies toward waste containment (Leal Filho et al., 2024a). However, it can be a risk to the SDGs when exporting waste and used products to developing economies is unregulated (Garcia-Saravia Ortiz-de-Montellano et al., 2023).

The issue of waste is paramount, as human activities are among the leading producers of pollution (Vardopoulos et al., 2021). During the pandemic, the strong propensity for online shopping drove an increasing use of packaging, including non-biodegradable packaging (de Oliveira et al., 2021). Consumers have varied behaviours in managing plastic packaging waste, with the main motivations behind these behaviours including environmental concerns and ecological values, but the lack of knowledge about recycling and the environmental characteristics of packaging is a significant barrier (Fogt Jacobsen et al., 2022). In this context, it becomes relevant to consider consumers' opinions since personal beliefs influence the choices made (Sokolova et al., 2023). Table 1 presents an overview of some of the challenges associated with package waste.

This table reflects some of the diverse challenges that industries, governments, and consumers face in managing waste packaging effectively.

Some alternative solutions are being investigated to replace single-use plastic with coated paper, for example, to meet the growing demand for more environmentally friendly packaging (Adibi et al., 2023), or how the use of bio-based materials for packaging shows significant emission reductions compared to the use of conventional packaging materials (Firoozi Nejad et al., 2021). Another material that has been attempted is packaging glass, which impacts the use of natural resources and energy (Furszyfer Del Rio et al., 2022). However, each type of material has distinct properties that affect its environmental impact: plastic provides protection but requires special attention regarding recycling; glass is easily recyclable but can be heavy to transport; metal is recyclable, but its recycling requires energy; and paper is biodegradable, but its use can contribute to deforestation (Otto et al., 2021).

Therefore, it becomes essential to increase separate collection and improve the efficiency of treatment plants (Bala et al., 2020), as technological progress is vital to identifying circular solutions (Larrain et al., 2021). In this regard, it is important to investigate consumer perceptions of packaging and the acceptance and use of new sustainable technologies in this area (Brennan et al., 2021).

Quantitative tools can significantly enhance the optimisation of European waste management by leveraging data and analytical techniques to improve efficiency, reduce costs, and minimise environmental impacts. Data Envelopment Analysis (DEA) can focus on the redistribution of materials instead of processing (Dyckhoff et al., 2024). Integrating DEA analysis as part of environmental and economic performance assessment in municipal waste management systems illustrates the importance of taking an integrated perspective to optimise the efficiency of waste management systems (Lombardi et al., 2021) and that of waste packaging (Sarra et al., 2017). In this regard, the analysis of the efficiency of European countries in plastic management in the European context aims at the sustainable management of packaging waste (Robaina et al., 2020). The advantage of the Multi-Criteria

Table 1 Some challenges associated with package waste. *Source*: authors

Challenge	Description
Increasing volume of waste	As consumerism rises, more packaging waste is generated, making it difficult to manage without overwhelming waste management systems
Material complexity	Packaging is often made from multiple materials (plastic, metal, glass, etc.), making it hard to separate and recycle
Contamination in recycling	Improper sorting of waste (e.g., food contamination) reduces the quality of recyclables, limiting their reuse
Lack of standardized recycling systems	Recycling rules vary across regions, causing confusion for consumers and reducing the efficiency of recycling programs
Plastic pollution	Plastic packaging, especially single-use plastics, is a significant environmental hazard due to its slow degradation in nature
Limited market for recycled materials	There is often a low demand for recycled packaging materials, which limits the financial incentives for recycling
Cost of waste management	Collecting, sorting, and recycling packaging waste is expensive and can strain municipal waste management budgets
Consumer behavior	Low public awareness or lack of motivation to properly dispose of waste leads to higher levels of litter and improper recycling
Extended producer responsibility	Many producers are not held accountable for the environmental impact of their packaging, placing the burden on governments and consumers
Technological limitations	Lack of advanced technology in some regions hinders efficient waste management, recycling processes, and innovation in sustainable packaging
Regulatory challenges	Inconsistent regulations across countries or regions can make it difficult to establish effective packaging waste management policies and practices
Circular economy integration	Shifting from a linear "take-make-dispose" model to a circular economy where packaging materials are reused or recycled requires significant structural changes
Biodegradable vs. non-biodegradable confusion	The market includes both biodegradable and non-biodegradable packaging materials, and consumers often do not know how to dispose of these correctly
Innovation lag	The development of alternative, eco-friendly packaging materials lags behind the production of traditional, environmentally harmful packaging

Decision Analysis (MCDA) is its flexibility and ability to provide assessments on the degree of sustainability among different alternatives (D'Adamo et al., 2023). Social aspects emerge as critical in waste management and packaging (Haslinger et al., 2024). Still nevertheless, it is also crucial to combine different methodologies, such as life cycle analysis and MCDA (Desole et al., 2024). MCDA is also used to compare the performance of European countries to assess which ones tend most to achieve CE targets (D'Adamo et al., 2024b). Therefore, the objective of this paper is to support the management of packaging waste toward sustainable development using two methodologies often used separately, MCDA and DEA. The former to identify the best strategies to make waste management more efficient and sustainable, the latter to assess its performance at the European level. In our view, this dual approach represents one of the novelties of this work.

The research objectives (ROs) are:

- RO1. Identify alternatives that outline the most accurate and sustainable strategy based on appropriate criteria through MCDA by involving academic and industrial experts.
- RO2. Identify the most efficient European countries in the packaging waste management process through DEA analysis geared towards maximising packaging recycling and recovery.

Answering these research questions is essential to the future of a more responsible and sustainable society. In fact, European member states have dedicated special attention to diverting waste from landfills. Packaging waste was particularly critical due to the growing environmental impacts and costs and the possibility of using this waste as a resource.

This paper is structured as follows. Section 2 provides the details on the methods used. Section 3 presents the results, which are discussed in Sect. 4. Section 5 provides the main conclusions from the paper and outlines some areas for further research.

2 Methodology

Two tools were used to gather and analyse existing research on packaging waste management in Europe: Multi-Criteria Decision Analysis and (MCDA) and Data Envelopment Analysis (DEA). The following section describes the MCDA (Sect. 2.1) and DEA (Sect. 2.2) geared towards achieving the two distinct ROs.

2.1 Multi-criteria decision analysis

MCDA is a methodology that evaluates and compares multiple criteria to make decisions in complex situations (D'Adamo et al., 2023; Dhaarna & Devadas, 2024; Khan & Gupta, 2024). Experts are selected, and then alternatives and criteria are defined. This method allows RO1 to be framed.

2.1.1 Selection of experts

A careful and diverse approach was taken when selecting experts to compile the evaluations for the alternatives and criteria. Two distinct groups of categories were identified: experts from industry and those with academic backgrounds. Ten participants were chosen from the experts, divided equally into five industrial experts denoted EI1, EI2, EI3, EI4, and EI5, and five academic experts denoted EA1, EA2, EA3, ES4, and EA5. It is noteworthy that among the ten experts selected, four are women, thus ensuring a relatively diverse and inclusive representation. The selection process was initiated during January and February 2024, when they were provided with an Excel file to conduct the analysis. This timing choice ensured adequate participation and proper time management within the project. Notably, the survey was divided into two distinct and sequential phases: the first aimed at collecting the criteria weights and the second at obtaining the criteria values for each alternative. In accordance with the literature (Saaty, 2008), the selection of weights was done through the Analytic Hierarchy Process (AHP). In this regard, the scale from 1 to 9 was evaluated (Table A1). Experts were informed that their contributions would be assessed and accepted only if the assignment of weights was consistent, according to the consistency ratio. In contrast, there were no verification tools to evaluate the assignment of values to the criteria. The experts had the opportunity to assign a rating from 1 to 10 (Almanza Floyd et al., 2024; D'Adamo et al., 2023). The industrial experts were contacted through social channels such as LinkedIn or e-mail. The selected industrial experts are Italian, but they have a work profile that includes exporting. Academics were selected on Scopus and then contacted using the same approach. These experts have an international profile. All experts have at least ten years of experience and interest in sustainable packaging (Table A2). Both phases involved data collection using an Excel file. The competitiveness value was obtained from the product between a row vector and a column vector for each alternative. The alternative that received the highest score was found to be the most competitive option for achieving more sustainable packaging.

2.1.2 Description of alternatives

Eight alternatives were identified to evaluate different sustainable packaging strategies representing distinct and innovative approaches to favouring sustainable approaches over less environmentally conscious practices (Table 2). This choice was made through a mix of what was found in the literature (see Sect. 1). To receive initial feedback, the alternatives were reviewed by both an academic and an industrial expert.

2.1.3 Description of criteria

Criteria analysis includes environmental sustainability, focusing on the durability and reusability of packaging, its eco-friendly design, and green production processes. The main objective is to minimise environmental impact throughout the product's life cycle, promoting waste reduction and responsible use of natural resources. It is also of paramount importance to consider economic sustainability, focusing on the added value represented by the green premium and the impact on brand reputation. These aspects reflect the importance consumers attach to sustainable packaging and its impact on the company's overall image,

Table 2 Description of alternatives

	Alternatives	Description
A1	Returnable container	Returnable packaging return system
A2	Natural fibres	Packaging based on natural fibres
A3	Recycled materials	Packaging made from recycled materials
A4	Sustainable transportation	Sustainable transportation with a focus on energy efficiency
A5	Human conditions	Packaging produced with respect for human conditions and workers' rights
A6	Digitisation	Automation and process digitisation in the packaging industry
A7	Customer relations	Customer relationship management as part of packaging sustainability strategy
A8	Landfill	Disposal of product waste to landfill

shaping consumers' perceptions of its environmental commitment. An additional focus is on social sustainability, highlighted by the impact on social welfare and packaging traceability throughout the supply chain. They explore packaging's influence on respect for workers' rights and transparency, promoting safe working conditions and ethical supply chain management. In summary, logistics optimisation and waste management are key aspects, including criteria such as optimisation and safe delivery, along with packaging end-of-life management. The goal is to improve logistics efficiency, reduce carbon emissions, and promote responsible disposal and recycling practices, helping to mitigate the overall environmental impact of packaging. Nine criteria were identified (Table 3), and the approach used was the one that occurred for checking on alternatives. No substantial changes emerged for both this step and the previous one; detailed descriptions of the options and criteria were added for comparison purposes.

2.2 Data envelopment analysis

DEA is a method widely used in the literature in sustainability contexts and specifically on waste management in the European context (Chioatto et al., 2024; D'Adamo et al., 2024a). DEA is a nonparametric technique for measuring the relative efficiency of organisational units. The main strength of the methodology lies in its ability to capture the interaction between multiple inputs and outputs. This process cannot be satisfactorily probed through traditional efficiency analysis. The advantage of DEA is that it produces an aggregate measure of efficiency for each unit considered, using multiple inputs and outputs to allow units to be ranked from most efficient to least efficient (Charnes et al., 1997). Its main drawback is that the efficiency value attributed to each unit is relative; that is, it depends on the efficiency of the other units that are part of the sample. For the specific RO2 objective, i.e., ranking European countries in the packaging waste management process, the output-oriented DEA analysis of maximising packaging recycling and recovery is applied in this paper. In the literature, DEA analysis reveals inefficiencies and provides valuable insights for improving waste management systems, promoting more significant economic and environmental efficiency (Daraio et al., 2024; Halkos & Petrou, 2019; Molinos-Senante et al., 2024). The models used to analyse efficiency in packaging waste recycling and recovery were developed with an output-oriented approach and include two distinct approaches: sustainable and technical, both designed in the context of the European Union using Eurostat data. To fully understand how they work, the Technical and Sustainable Models of Recycling will be examined first and then those related to Recovery. The former are illustrated in Fig. 1 (Sustainable Model—Recycling) and Fig. 2 (Technical Model—Recycling), respectively. In the Sustainable Model—Recycling, the inputs considered include investment, percentage of use in CE sectors, and CO_2 emissions. The primary objective of these models is to maximise the total amount of waste packaging recycled, reflecting the European Union's commitment to more sustainable management of packaging waste.

In the Technical Model—Recycling, the analysis is extended by also including the five generated waste packaging categories as separate inputs: paper, glass, plastic, wood and metal. This more detailed approach allows a specific assessment of recycling dynamics by also considering material categories, while still maintaining the same basic inputs of investment, percentage of use in circular economy sectors, and CO_2 emissions.

The Technical and Sustainable Models of Recovery are presented in Fig. 3 (Sustainable Model—Recovery) and Fig. 4 (Technical Model—Recovery). Again, the Sustainable Model—Recovery considers the same investment inputs, percentage of use in circular

Table 3 Description of criteria

	Criteria	Description
C1	Durability and reusability	The ability of the packaging to withstand multiple uses and the ease with which it can be reused without compromising its functionality
C2	Ecological design	The visual appearance of packaging is attentive to the balance of ecosystems
C3	Green premium	Added value that consumers are willing to pay extra for more sustainable packaging, considering all product features (e.g., materials used and environmentally friendly transportation practices)
C4	Brand reputation	The effect of packaging on overall brand perception, including how it affects corporate reputation and consumer perception of the company's environmental commitment
C5	Green production process	Packaging production practices to minimise environmental pollution during all stages of the production process
C6	End of life	Measurement of the amount of waste generated by packaging throughout its life cycle, from production to final disposal
C7	Optimisation and security of delivery	Optimal size of packaging and safety practices during the delivery phase to minimise waste and ensure product safety
C8	Social impact	Effect of packaging on respect for the rights and conditions of workers involved in its production
C9	Traceability	Evaluation of the ability to track packaging throughout the entire production cycle, from its creation to reaching the end consumer

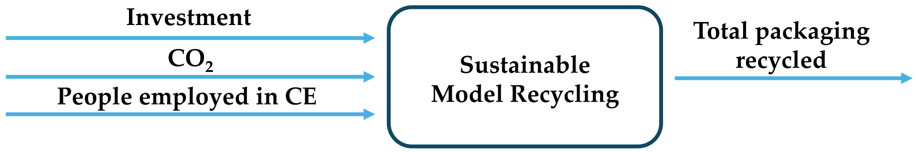

Fig. 1 Input & output sustainable model—recycled

Fig. 2 Input & output technical model—recycled

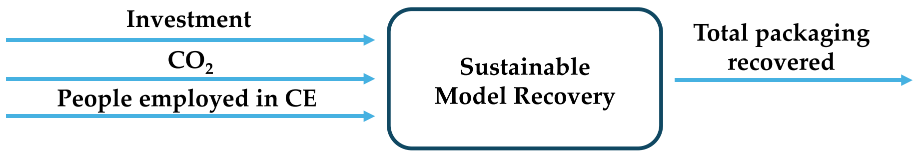

Fig. 3 Input & output sustainable model—recovery

Fig. 4 Input & output technical model—recovery

economy sectors, and CO_2 emissions to maximise the total amount of waste packaging recovered.

The Technical Model—Recovery, also allows for an extended analysis of the five waste packaging categories considered above.

In both cases, sustainable and technical, the goal remains to optimise resource use efficiency to maximise the total amount of waste packaging recycled and recovered. The output-oriented approach emphasises the priority given to maximising the desired outputs over the inputs used, representing a pragmatic method for evaluating and improving packaging waste management practices within the EU. Preliminary test results capable of assessing the suitability of this methodology were positive for analysing the research objective—Table A3.

The data used are taken from Eurostat and refer to the period from 2016 to 2020, thus covering 5 years. Considering the number of alternatives to be 27 (i.e., European countries), 135 data points are considered for each single variable. Figure A1 shows that the total packaging generated in 2020 is 149.8 kg per capita and shows an increase over the years (139.6 kg per capita in 2016). As for the recovered and recycled amounts, they show fluctuating trends over the years: from 110.5 to 116.4 kg per capita the recovered share and from 91.8 to 93.7 kg per capita the recycled share from 2016 to 2020. However, there is a decrease in these values in 2020 compared to 2019.

3 Results

This section presents the strategic analysis (Sect. 3.1) to answer RO1 and the efficiency analysis (Sect. 3.2) to provide answers to RO2.

3.1 Results–strategic analysis

3.1.1 Aggregation of weights

Before proceeding with the analysis of the results, it is necessary to aggregate the different weights given by individual experts in Tables A4–A13. Then, the results derived from the AHP are obtained as an equally weighted average of the different contributions—Table 4. The last column of this table identifies the components of the row vector. The CR of all the pairwise comparisons was fit and less than 0.10.

The results show differences in opinions and sensitivities towards different criteria. For example, EA3 gives considerable weight to durability and reusability of packaging (C1) with a relative weight of 0.246, while EA5 seems to give more importance to Green Premium (C3) with a weight of 0.257. At the same time, industry experts also manifest divergences in their assessments, with EI7 giving a score of 0.243 to social impact (C8) and EI10 giving a weight of 0.204 to packaging traceability (C9). The results show that criterion C3 is chosen as the most relevant by three experts, while C5 and C1 are chosen by two experts. In contrast, all experts assigned lower relevance to criterion C7. The overall analysis of the weights shows that Green Premium (C3) excels with 0.177, followed by green production process (C5) with 0.147, waste management (C6) with 0.145, and durability and reusability (C1) with 0.136. These four criteria thus weigh three-fifths of the

Table 4 Aggregation of expert weights

	EA1	EA2	EA3	EA4	EA5	EI6	EI7	EI8	EI9	EI10	Row vector
C1	0.163	0.105	*0.246*	0.061	0.136	*0.212*	0.195	0.173	**0.032**	0.035	0.136
C2	0.040	0.105	0.043	0.046	0.067	0.100	**0.032**	0.066	0.037	0.068	**0.060**
C3	0.216	0.188	0.180	0.144	*0.257*	0.163	0.039	*0.296*	*0.252*	**0.030**	*0.177*
C4	0.054	0.066	0.058	0.202	0.098	0.143	0.050	0.053	0.081	0.104	0.091
C5	0.079	*0.160*	0.104	*0.275*	0.127	0.066	0.168	0.138	0.167	0.183	0.147
C6	*0.264*	0.137	0.208	0.146	0.132	0.110	0.123	0.157	0.121	0.052	0.145
C7	**0.033**	**0.056**	**0.036**	**0.033**	**0.048**	0.076	0.056	**0.032**	0.154	0.128	0.065
C8	0.104	0.105	0.076	0.053	0.057	**0.044**	*0.243*	0.045	0.104	0.195	0.103
C9	0.047	0.077	0.049	0.039	0.078	0.087	0.093	0.039	0.052	*0.204*	0.076

Bold: Minimum value, Italic: Maximum value total weight. The result related to Green Premium may depend on consumers' increasing focus on environmentally friendly and sustainable products.

Instead, closing the ranking are the criteria optimisation and security of delivery (C7) with 0.065 and ecological design (C2) with 0.060. This overview suggests the need for a balance between environmental, social, and economic aspects in the design and evaluation of sustainable packaging to ensure an overall strategy that meets the needs of all stakeholders. Table A14 shows that there are thus differences between the judgments of academics and those of industrialists. In fact, with the exception of the criterion most relevant to both groups of experts (C3), all other criteria occupy a different position of relevance. Academics place less relevance on criterion C7, industrialists on criterion C2. The biggest difference in ranking concerns criterion C6, placed second by academics and fifth by industrialists. And finally, the range between the highest and lowest value is smaller for industrialists than for academics (0.095 vs. 0.156).

3.1.2 Aggregation of values

After the row vector is defined, the column vector is composed. In the second phase of the survey, the same experts involved in the previous phase were asked to assign a value to each alternative for each criterion (Table A15–A24). The percentage distribution of votes for the different alternatives offers interesting insights into the acceptance and evaluation of various approaches to sustainable packaging. With a total of 720 ratings from ten experts (Figure A2), a preference for higher ratings clearly emerges, with 22.4% of the votes given for score 9, 21% for score 8, and 14.6% for score 10, together accounting for 58% of the responses. What is even more significant is that 81.2% of the ratings are in the 6–10 range, suggesting a generalised acceptance of the proposed alternatives, at least in their most favourable version. In fact, alternative A8, which proposes landfilling of waste, shows a distribution of evaluations toward low scores, with 58% of evaluations assigned to score 1 (Table A25). The result is not surprising, as there is inevitably a negative perception of landfilling as an unsustainable solution. We proceed below to aggregate the different values, identifying an average value in consideration that the experts all have equal importance. This makes it possible to calculate the column vector for each alternative (Table 5).

The data in Table 5 make it clear that alternative A2 (Natural Fibres) is a particularly promising choice, with high ratings for several criteria. For example, experts gave an average score of 9.00 for criterion C3 (Green Premium), indicating that the use of natural fibres is considered a significant factor in adding value and appeal to the product. Looking at

Table 5 Aggregation of expert values

	A1	A2	A3	A4	A5	A6	A7	A8
C1	8.50	8.20	7.10	6.3	6.90	6.3	7.60	1.60
C2	7.20	9.00	8.00	6.40	7.60	6.3	7.00	2.50
C3	7.80	9.00	7.80	7.80	9.50	6.90	9.00	1.50
C4	7.80	9.00	8.30	7.80	9.30	6.50	9.20	1.50
C5	7.60	8.80	8.20	7.00	7.90	7.60	7.50	2.60
C6	8.30	9.20	8.60	6.60	7.50	5.90	7.40	2.80
C7	8.00	8.50	8.00	8.20	7.80	7.50	7.90	1.60
C8	6.90	8.40	7.90	6.50	9.60	6.90	7.80	1.50
C9	7.50	8.50	7.90	7.40	7.70	8.40	7.40	1.60

alternative A2, it received an average score of 8.80 for criterion C5 (Green Production Process), suggesting that the use of this material is considered highly sustainable during all stages of the production process. In contrast, alternative A8 (Landfill) shows very low ratings on all criteria considered. For example, for criterion C1 (Durability and Reusability), alternative A8 received an average score of only 1.60, reiterating that disposal of product waste to landfill is not seen as an efficient solution to promote reusability of packaging.

3.1.3 Sustainability value

In the analysis of the results of the ranking of alternatives to improve the strategy for sustainable packaging, the values obtained from the row vector (Table 4) for the column vector (Table 5) were considered, resulting in what is shown in Fig. 5. The main objective of this step was to identify the most suitable alternative to improve the strategy for sustainable packaging, taking into account the weights assigned to the criteria and the values given to the experts. In this regard, it is also useful to propose a disaggregation analysis to understand the contribution of the individual criteria (Table A26).

The results see alternative A2 excel with 8.76, thus recording a very high value and not far from the maximum rating of 10. This performance is easily explained by considering the values assigned to the three criteria considered most relevant. However, there are several alternatives that have very significant values that are close to the rating of 8. In fact, the second place is occupied by human conditions (A5) with 8.25, which precedes recycled materials (A3) with 7.97, customer relations (A7) with 7.94, and returnable vacuum (A1) with 7.80. Turning out to have less relevant performance but still close to 7 are the other

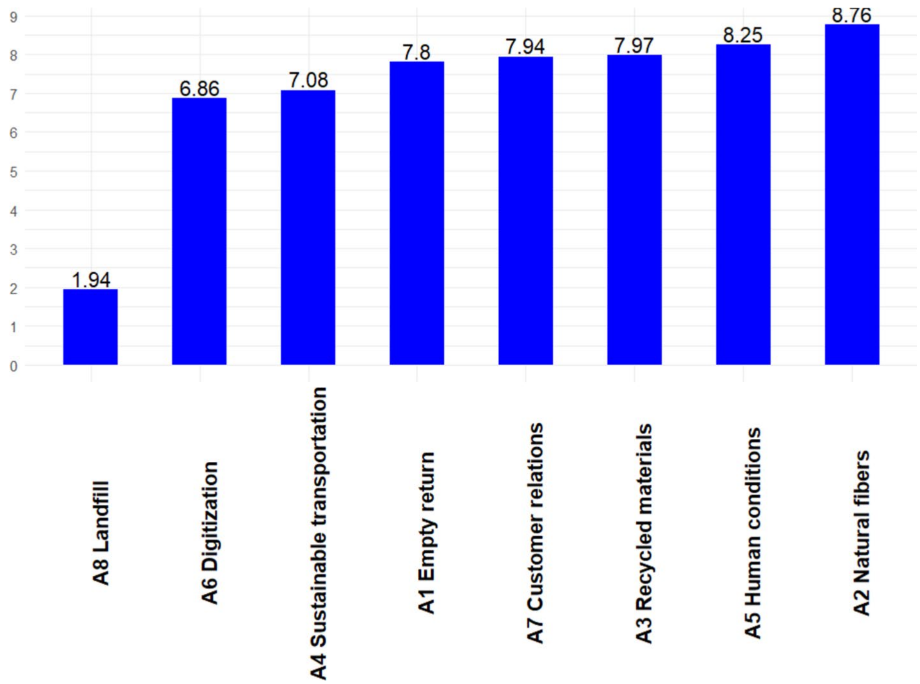

Fig. 5 Value of sustainability

two alternatives deemed sustainable: sustainable transportation (A4) with 7.08 and digitisation (A6) with 6.86. The value of A6 indicates that life cycle analyses probably need to better assess the relationship that exists between sustainability and digitization. The ranking is closed by landfill (A8), which was rated very low, with a value close to 2. In order to give solidity to the results obtained, an alternative context was considered in which the weights were all considered equally relevant. Interestingly, the ranking remained the same even with average weights, suggesting that the alternatives were evaluated consistently, regardless of the distribution of weights (Table 6).

3.2 Results—efficiency analysis

Through the application of DEA, the levels of efficiency in packaging waste management in European Union countries were evaluated. The twenty-seven member countries were considered as organisational units in the models presented earlier, which include two approaches, sustainable and technical. These models considered a number of key indicators, including investment in the sector, percentage of employment in circular sectors, and CO_2 emissions. The technical model also included the five categories of generated packaging waste as additional inputs. Analysis through the DEA provided detailed results on the countries' efficiency in packaging waste recycling and recovery, allowing for the identification of the most efficient countries and those that could benefit from improved interventions (Table 7).

In Figs. 6 and 7, Spearman's correlation between the two recycling models and the two recovery models was analysed in order to understand possible relationships between different packaging waste management strategies and their impacts on overall efficiency. Analysis of the efficiency performance of European Union countries in waste recycling and recovery revealed a number of interesting trends and disparities. In both cases, a significant correlation (0.74 and 0.68) emerges between the efficiency of sustainable and technical models, indicating the importance of an integrated strategy to address waste management challenges.

In the case of the analysis of the efficiency performance of European Union countries in recycling waste packaging, countries such as Luxembourg, Belgium, Spain, Greece and Sweden stand out for their effectiveness in recycling waste packaging, suggesting that targeted investments in infrastructure and innovative technologies, along with public

Table 6 Sustainability value

Alternatives	Ranking	Sustainability value (different weights)	Sustainability value (equal weights)
A2	1	*8.76*	*8.73*
A5	2	8.25	8.20
A3	3	7.97	7.98
A7	4	7.94	7.87
A1	5	7.80	7.73
A4	6	7.08	7.11
A6	7	6.86	6.92
A8	8	**1.94**	**1.91**

Bold: Minimum value, Italic: Maximum value

Table 7 Ranking for the four models for the 27 EU countries

Rkg	Sustainable recycling		Technical recycling		Sustainable recovering		Technical recovering	
1°	IF	0.988	LU	0.989	AT	0.984	AT	0.998
2°	LU	0.986	ES	0.985	LU	0.968	FI	0.994
3°	BE	0.984	EL	0.984	IF	0.955	LU	0.993
4°	YES	0.967	BE	0.982	FI	0.950	ES	0.987
5°	NL	0.967	BG	0.980	ES	0.918	BE	0.987
6°	ES	0.960	CY	0.974	FR	0.916	EL	0.980
7°	EL	0.960	IF	0.973	EN	0.914	CY	0.980
8°	RO	0.946	AT	0.967	NL	0.903	BG	0.977
9°	CZ	0.943	YES	0.949	BE	0.890	NL	0.973
10°	AT	0.923	NL	0.948	YES	0.882	IF	0.960
11°	EN	0.915	HR	0.945	IE	0.878	YES	0.953
12°	SK	0.911	SK	0.935	DE	0.856	HR	0.942
13°	CY	0.901	RO	0.882	EL	0.801	SK	0.933
14°	IE	0.898	CZ	0.877	RO	0.787	IE	0.931
15°	FI	0.892	PT	0.875	PT	0.761	DK	0.931
16°	DK	0.885	DK	0.862	SK	0.750	FR	0.917
17°	DE	0.868	LV	0.848	LV	0.734	EN	0.914
18°	FR	0.859	EN	0.826	DK	0.731	LV	0.884
19°	BG	0.828	FR	0.820	HR	0.723	CZ	0.870
20°	LT	0.806	IE	0.817	HU	0.654	PT	0.863
21°	LV	0.798	FI	0.804	CY	0.644	DE	0.856
22°	PT	0.784	DE	0.716	EE	0.632	RO	0.856
23°	EE	0.783	HU	0.703	BG	0.615	HU	0.776
24°	HR	0.770	LT	0.701	LT	0.614	EE	0.775
25°	PL	0.720	MT	0.677	CZ	0.594	LT	0.741
26°	MT	0.672	EE	0.578	MT	0.572	MT	0.590
27°	HU	0.641	PL	0.572	PL	0.450	PL	0.543

Belgium (BE), Bulgaria (BG), Czechia (CZ), Denmark (DK), Germany (DE), Estonia (EE), Ireland (IE), Greece (EL), Spain (ES), France (FR), Croatia (HR), Italy (IT), Cyprus (CY), Latvia (LV), Lithuania (LT), Luxembourg (LU), Hungary (HU), Malta (MT), Netherlands (NL), Austria (AT), Poland (PL), Portugal (PT), Romania (RO), Slovenia (SI), Slovakia (SK), Finland (FI), Sweden (SE)

awareness campaigns, have played a key role in their successes. Countries such as Bulgaria and Croatia show a good level of efficiency in the technical model but have room for improvement in the sustainable model, indicating the need for more attention to practices related to sustainability and the circular economy.

In the case of recovery, however, countries such as Austria, Luxembourg, Finland, Spain, and Sweden emerge as leaders in both sustainable and technical model efficiency, thanks to sound policies and significant investments. In contrast, countries such as Latvia, Portugal, Czech Republic, Estonia, Hungary, Lithuania, Malta, Poland and Denmark could benefit from more integrated policies to improve their overall performance in waste management. Countries such as Germany, Italy, and France show greater efficiency in the sustainability model than in the technical model, suggesting the need to focus on strategies to improve the overall

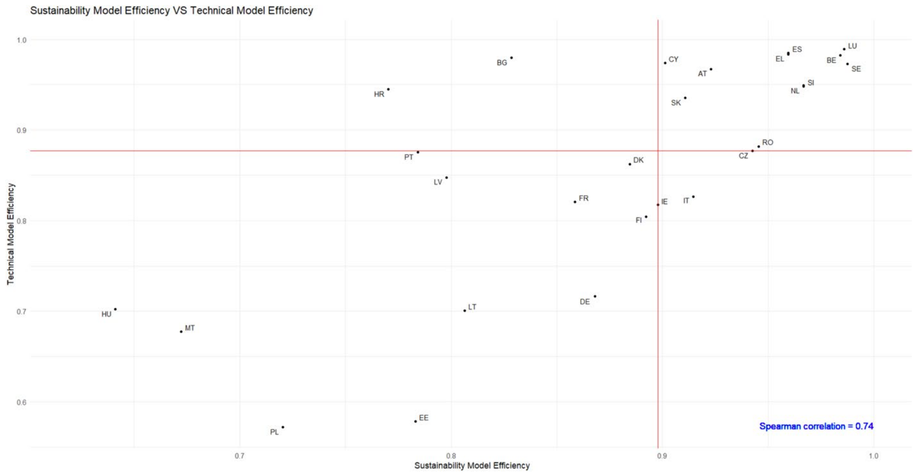

Fig. 6 Comparison of sustainable model and technical model—recycling

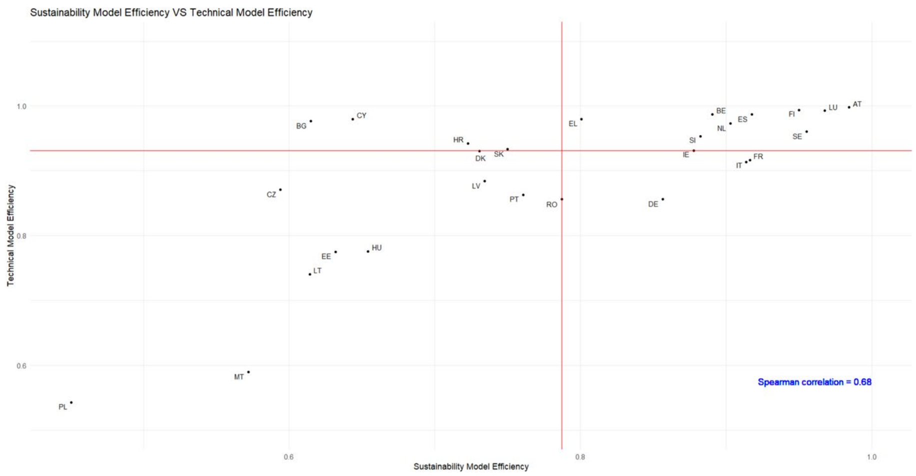

Fig. 7 Comparison of sustainable model and technical model—recovery

efficiency of waste management. These analyses provide a detailed picture of the performance of different EU countries in waste management and can inform future policy formulation to promote more efficient and sustainable waste management across the European Union. To obtain a clearer and more comprehensive visualisation of efficiency ranges related to recovery and recycling, the following Figs. 8 and 9 show a map of the European Union that illustrates its average efficiency levels achieved for both recycling and recovery of waste in the packaging sector.

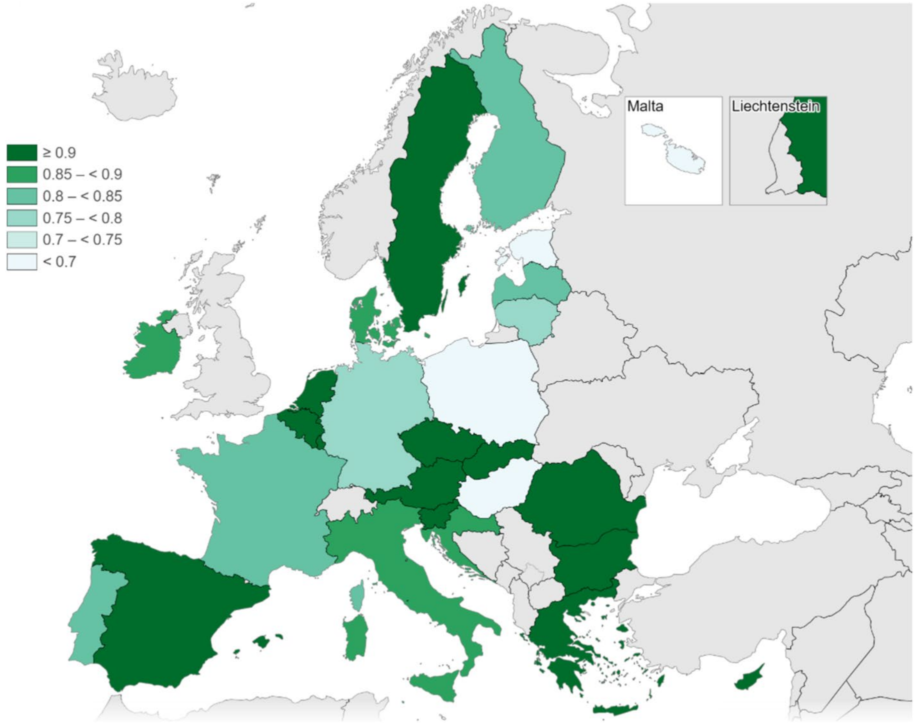

Fig. 8 Efficiency ranges—recycling

4 Discussion

To address the differences in packaging waste management across European countries and support the aim of Europe being resilient and sustainable, a structured and comparative analysis is essential. The methodology should encompass data harmonization, contextual analysis, a robust comparative framework, and policy assessment. Current procedures used among European countries show differences that do not allow for aggregation. If circular material use is assessed, countries such as Austria, Belgium, Estonia, France, Germany, Italy, Luxembourg, and the Netherlands stand out (Fan et al., 2024). When considering the recycling rate, the Netherlands, Belgium, and Austria stand out (Milanović et al., 2022), and in terms of patents in the CE, Italy, the Netherlands, Spain, and Belgium emerge for best practices (Marino & Pariso, 2020). Analyses on CE models see Belgium prevailing in basic and alternative scenarios, followed by Italy and the Netherlands, respectively. Important performances emerge for France, Latvia, Croatia, Austria, and Sweden (D'Adamo et al., 2024c). Weak results are seen in Cyprus and Greece (Giannakitsidou et al., 2020). Given that the ranking of European countries in terms of packaging waste is not widespread in the literature, good performances for plastic packaging waste stand out for Belgium, the Netherlands, Luxembourg, the Czechia, and Finland (Vuk et al., 2023). The top five sees Luxembourg as the only country present in the 4 models, followed by Belgium and Spain appearing in 3 models and Austria, Sweden and Finland in 2 models (Table A27). It would therefore be useful to highlight the discrepancies between the results

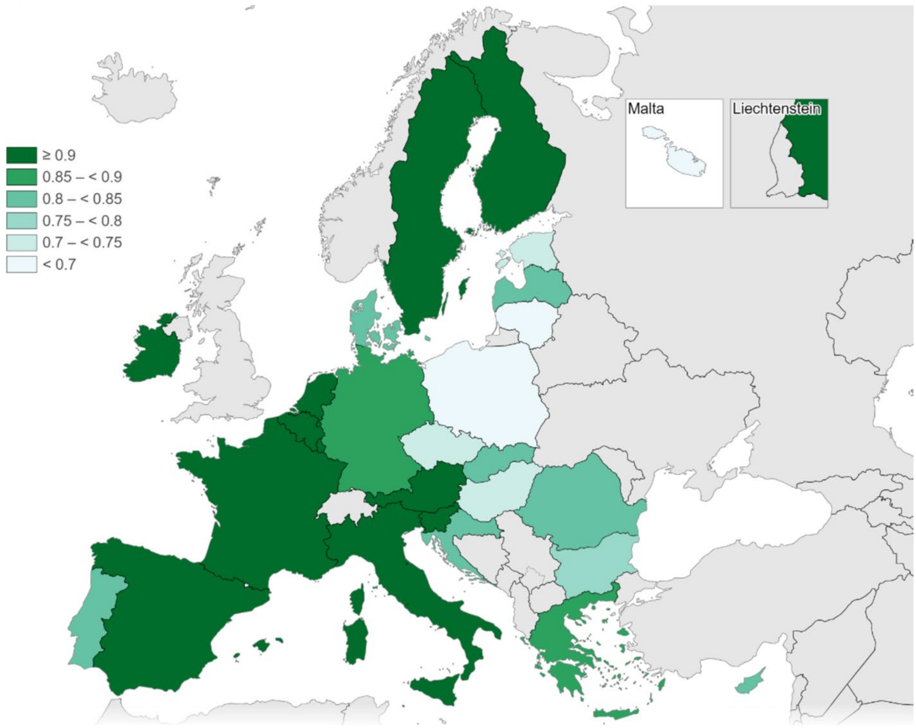

Fig. 9 Efficiency ranges—recovery

obtained through Eurostat (Table A28) and those presented in this research. In the technical recycling model, for example, Greece ranks third, while in the Eurostat ranking it only ranks 19th. Similarly, Bulgaria ranks fifth in the technical model, while in Eurostat's model it ranks seventeenth. This suggests that the DEA analysis, also considering sustainability indicators, recognises Greece and Bulgaria as virtuous countries. Another interesting observation concerns Spain, which ranks in the top five in both sustainable and technical models for recovery. However, in Eurostat's data, for recycling, it ranks among the top ten, while for recovery it ranks 15th. Further limitations point out that some data turn out to be incomplete or based on estimates and assumptions, and also incorrectly assigned (Warrings & Fellner, 2019).

A systematic literature review on sustainable packaging highlighted the need to focus on new materials, new technologies, and analytical methods to verify packaging performance (Sastre et al., 2022). Some authors have pointed out that the promotion and encouragement of sustainable packaging should be a priority for governments, with the introduction of strict environmental standards and careful monitoring of emissions (Zhang & Zhao, 2012). Experts in this paper have paid more attention to green economy models than to circular economy ones. In fact, according to the definition of the European Environment Agency, aspects emerge that recall the resilience of eco-systems, such as the use of natural fibres, and the relation to social welfare, such as respecting the human conditions of workers. In contrast, the use of recycled materials and empty return, while considered promising, have less relevance. These results that emphasise the relevance of natural fibres are consistent with some studies proposed in the literature (Aisyah et al., 2021; Ali et al., 2021; Imraan et al., 2023). Different raw materials and different coatings of natural-based packaging materials can be used, but the role of end-of-life options should also be framed in this context (Kóczán & Pásztory, 2024). Some physical and chemical treatments have been found to enhance the strength of bio-based packaging for commercialisation (Pulikkalparambil et al., 2023), and this choice requires a comprehensive life cycle assessment, which is critical for sustainability assessments (Alhazmi et al., 2021; Sazdovski et al., 2021). Another aspect that emerges is the training that staff must have on the relevance of sustainable packaging materials (Wandosell et al., 2021), important for strengthening the social component (Almanza Floyd et al., 2024) and the role of human beings (D'Adamo et al., 2024a). Sustainable choices involve major investments in new machinery; however, legislative aspects should favour circular choices (Weinrich et al., 2024). In this context, an important role is played by the consumer, who should recognise an added value to eco-friendly approaches in addition to making sustainable choices (Cao & Xu, 2023; Mahmoud et al., 2022). This work highlights a strategic role that will be played by green premium. To this end, stakeholder engagement is crucial (D'Adamo, 2023; Giacomarra et al., 2020) with a key-role played by young generations (Leal Filho et al., 2024b). So are collaborations between industry and academia, as well as within them, to foster multidisciplinary approaches that encourage product-service system design and circular design with a clear policy framework (Bradley & Corsini, 2023).

5 Conclusions

The sustainable management of waste packaging in the European context is a crucial issue in efforts to promote SDG 12. European data show there was an increase in waste generation during the period from 2016 to 2020, as well as a decrease in material recovery and recycling in 2020 when compared to the previous year. This shift inevitably drives the urgent need for more effective and sustainable strategies in packaging waste management. The practical implications of this work are many. Most important is the need to identify the best strategy related to packaging waste, moving from classic packaging to sustainable packaging. To promote the sustainability factor of packaging, manufacturers should evaluate some main factors, such as whether the product actually needs to be packaged and the minimum amount of packaging needed to maintain the appearance and quality of the product. Another aspect should relate to the packaging design process related to some critical elements such as mass, volume, and optimal use of raw materials. Only in some cases, packaging must be disposed of and may end up incinerated or dumped in landfills.

In addition, the results show a worryingly fragmented performance in Europe, with some countries standing out as top performers by demonstrating above-average performance. At the same time, other countries are far from achieving at least acceptable results. Instead, there is a case for an integrated vision of packaging waste management at the European level to foster a circular model of municipal waste management to minimize landfilling and other environmentally harmful practices. In this way it will be possible to thereby stimulating the development of a circular waste management model and new sustainable communities in line with broader sustainability goals.

The RO1 results underscore that green premium is an essential criterion, since value sharing is achieved when all stakeholders assign relevance to sustainable choices, even from an economic perspective. Different alternatives to landfill are encouraged by both academics and industrialists, indicating the urgency for change. The use of natural fibres and respect for human conditions rate highly, highlighting the multiple dimensions that sustainability pursues. These aspects relate more to the green economy than the circular economy.

The RO2 results show how Sweden tops the recycling rankings for the sustainable model and Luxembourg for the technological model; at the same time, Austria prevails in the recovery ranking for both models. The top five results also highlight the performance of Belgium, Spain, and Finland. These performances are different from those proposed by Eurostat because they incorporate additional dimensions.

This paper has some limitations. The first one is that the work is limited by the availability and quality of data on waste packaging and recycling rates across different European countries. Also, the findings are specific to the European context and not generalizable to other regions with different waste management infrastructures and policies.

Moreover, differences in waste management practices and regulations across European countries might lead to varied applicability of the results. Finally, the choice two of analytical methods could introduce biases or limitations. For instance, the efficiency analysis might rely on specific models that have inherent assumptions and limitations.

Some limitations of the work are that it could benefit from performance trend assessments on more data and on comparing DEA with other quantitative approaches such as MCDA to assess individual performance of European countries. It could also be useful to integrate new analyses by applying life cycle to different alternatives and a consumer analysis using a survey that could indicate personal preferences. The basic idea is that recycling supports sustainability more than the recovery steps according to the waste hierarchy however the pragmatic and not ideological solution identifies that only a life cycle analysis identifies the best solution. So, the optimal point in sustainability is composed of multiple end-of-life management models and different perspectives that can come from the methodological mix, which is the suggestion coming from this work.

This work suggests a pragmatic and non-ideological approach with respect to waste packaging. It is important for companies to bring their products to market and for consumers to satisfy their needs, but changes based on responsible behaviour are required for both. Similarly, packaging must enhance products and be used when necessary, and the mix of materials within the packaging could impact the quality of the recycled material. This is consistent with the outcome of this work that directs sustainable packaging toward green economy models and identifies stakeholder involvement.

Some further research is needed in respect of the investigation of new materials that can replace conventional plastics waste and are more environmentally friendly. Also, research is needed on enhancing the recyclability and reusability of packaging materials. Further works are also needed on strategies to reduce the amount of packaging used and comprehensive lifecycle assessments to identify the stages where waste can be minimised.

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Data availability The data used in this study can be procured from the corresponding author upon request.

Declarations

Conflict of interest We declare no conflict of interest.

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