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Research

Assessment of the circular economy indicators in the EU Member States

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Abstract
The major purpose of this research is to empirically assess the level of the circular economy in the EU Member States. The empirical research revealed that the major criteria for assessing the level of the circular economy in the EU, according to the experts, are material footprint, patents related to waste management and recycling, and material import dependency, while intra EU trade and private investment in the circular economy sector are considered least important. All the methods indicated Germany as the EU leader in the area of circular economy, Italy and the Netherlands also being high rated. The lowest ranks were estimated for Bulgaria, Romania, Finland and Estonia, which could improve their situation by adopting the best practices of the leading countries (e.g. use innovative business models at the stage of product development, strengthen cooperation between business companies, governmental agencies, NGOs and academic communities). Research limitations: subjective nature of the expert evaluation, which could lead to different indicator weights if similar research is conducted in other countries; insufficiency of the statistical data.

Article Highlights

- Assessment of circular economy should not be limited to the evaluation of waste generation and management.
- The EU circular economy leaders make effort to extend their regulatory framework, incentives and public awareness.
- Lowest-ranked countries should increase investment in R&D, promote green procurement and producer responsibility.

Keywords Circular economy · Circular economy indicators · Multiple-criteria methods · European Union

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1 Introduction

Relevance of the topic. After the European Parliament and the Council approved the 2021 EU Climate Law, which made legally binding a target of reducing emissions under the Paris Agreement adopted at the UN Climate Change Conference in 2015, and the European Green Deal launched by the European Commission in 2019, which aims "to transform the EU into a fair and prosperous society, with a modern resource-efficient and competitive economy with zero net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use", the attention to the issue of the green transition in the EU is increasing. The principles of circular economy are expected to facilitate the economic, social, and environmental problems encountered by modern societies. To accelerate the green transition, the European Commission presented the New Circular Economy Action Plan of 2022, and in 2023 approved the legal acts, which will ensure the transition towards circular economy. Circular economy is believed to contribute to waste reduction, pollution and climate change prevention, conservation of resources and security of their supply, and economic resilience. Therefore, it is extremely important not only to implement the principles of circular economy, but also to properly assess their impact, so that stakeholders can make reasonable decisions and develop effective strategies to promote the green transition. Nevertheless, despite a wealth of literature to discuss the circular economy indicators, a comprehensive assessment method has not yet been developed. The need to improve the assessment of the circular economy in the EU is also emphasised in the special report No. 17, submitted by the European Court of Auditors in 2023.

The research problem is formulated as a question: what indicators can be used to assess the level of circular economy in national economies? *The major purpose* of the research is to empirically assess the level of the circular economy in the EU Member States. To fulfil the defined purpose, the following *objectives* were raised: (1) to research the theoretical aspects of circular economy and reveal the most common criteria, which are used for measuring the level of circular economy; (2) to develop the circular economy assessment methodology and identify the indicators which represent particular criteria; (3) to empirically assess the level of the circular economy in the EU Member States.

Research methods:

1. Literature analysis, systematisation, and summarisation.
2. Secondary data analysis.
3. Weight estimation methods: the Entropy and expert evaluation.
4. Muti-criteria decision analysis: the PROMETHEE, SAW and TOPSIS methods.

The article is structured as follows: Sect. 2 discusses the concept of circular economy, provides the criteria representing the circular economy situation, highlights the areas critically affected by circular economy, and identifies the indicators which are commonly used for measuring circular economy; Sect. 3 describes the methodology, which was selected for assessing the circular economy situation in the EU Member States; Sect. 4 provides the empirical assessment of the level of the circular economy in the EU Member States.

2 Literature review

2.1 Theoretical aspects of the circular economy concept

Scientific literature and other sources note that circular economy is explained not only by highlighting the differences between the circular and linear economy models, but also by developing strategies towards circularity. Salguero-Puerta et al. [1] state that circular economy offers a 3R scheme—reduce, reuse, and recycle (3R), whereby waste is replaced with by-products, and circular economy allows for sustainability, maintenance of the economic value of resources, reduction of waste, turning waste into resources, and returning the resources to production processes [1]. These principles cover only waste management and minimisation strategies, but do not consider the concept of circular economy in principle. Liu et al. [2] argue that the current circular economy systems focus on designing products to be renewable and regenerative so that they can be used at their maximum value, and propose the 3R model to be developed to 6R (reuse, recycle, re-design, remanufacture, reduce, and recover). The new

principles reveal that attention must be focused not only on waste management, but also on the stages of product development, where a product is designed to be redeveloped, remade, and restored. This approach highlights the importance of *developing the market for secondary raw materials*. Kirchherr et al. [3] notice that researchers tend to extend the boundaries of the concept of circular economy not only from the 3R to the 6R, but even to the 9R strategies (see Fig. 1).

Figure 1 shows that the R9 strategy represents the lowest, while R0 represents the highest circularity, which implies that this system, like the waste hierarchy in the EU Waste Framework Directive, considers the preventive measures, such as refusal (R0 in Fig. 1), more desirable than waste disposal or secondary use. This approach is believed to reduce the negative environmental impact of waste generation and management, improve the efficiency of resources, and contribute to the objectives of circular economy. According to Kirchherr et al. [3], the major system is the 3R system, but it does not consider the concept of "recovery" of raw materials, which is inseparable from the concept of circular economy in particular scientific studies, and despite the fact that researchers tend to extend the systems beyond the 4R (reduce, reuse, recycle, and recover) up to 6R, or even 9R, the 4R system is the basis of these varieties [3].

When analysing the concept of circular economy, Remeikienė et al. [4] focus on 3 major dimensions—economic, environmental and social, and provide the advantages of each of them: in the economic sense, circular economy radically transforms the economic model based on mass production, mass consumption, and a lot of waste; in the environmental sense, circular economy promotes the sustainable use of all resources; in the social sense, circular economy promotes social well-being through using fewer resources and generating less waste, but extracting maximum value and maximum utility from resources and products.

Summarising, it can be stated that scientific literature contains a variety of the concepts of circular economy since circular economy can be assessed from different perspectives—environmental, social, and economic. The literature analysis suggests that the definition of circular economy often depends on a research purpose, problem, and the strategies proposed for solving the problem. Some researchers tend to emphasise the benefits of circular economy as a closed system, which aims to keep resources in circulation, thus reducing the need for virgin materials, extending a product lifecycle, and optimising the use of resources based on sharing, joint consumption, and industrial symbiosis. Others highlight social aspects and the relevance of justice, cooperation, education, and involvement, or state that circular economy is inseparable from environmental protection and is the basis for solving environmental problems. Thus, to identify the criteria which represent circular economy and allow for the multi-criteria analysis of the circular economy situation in different countries, this research considers the multi-sidedness of circular economy and its influence in different (economic, social, and environmental) areas.

2.2 Systematic approach towards the analysis of circular economy and its indicators

To fulfil the research purpose, it is necessary to identify the indicators which allow for comprehensive assessment of the circular economy situation in a particular country. Xijie et al. [5] argue that the issues of circular economy are analysed in many countries, but thus far no single indicator has been developed to comprehensively measure the level of circular economy. The fact that the level of circular economy is measured by including different indicators was also confirmed by

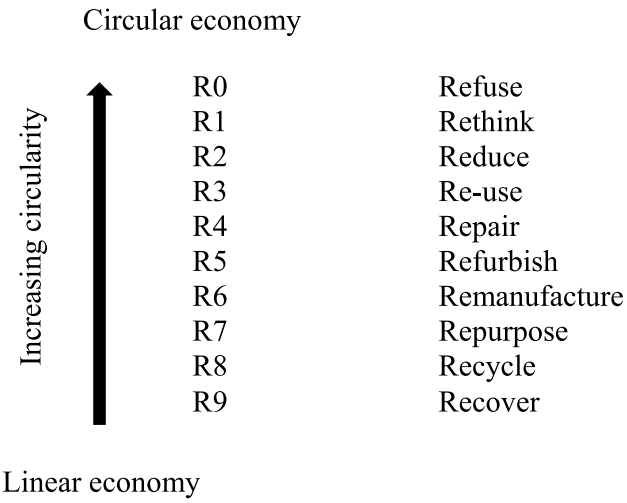


Fig. 1 The 9R system (Source: adapted by the authors from Kirchherr et al. [3])

the study of the OECD [6] conducted in 2021. The OECD [6] identified as many as 474 circular economy indicators, which reflect the progress in the area of circular economy (the research covered the period 2018–2020). The indicators were extracted from 27 circular economy studies, 8 of which were conducted at the national, 8—at the regional, and 11—at the local level [6]. Saidani et al. [7] note that researchers, industrialists, and policy makers globally agree that the circular economy-related data are needed to manage the transition at various systemic levels. Nevertheless, the study by these scientists is another proof that a unified system for assessing the level of circular economy has not yet been developed.

The European Environment Agency (EEA) [8] emphasises that the objectives of circular economy should be directed not only to waste recycling, but also to other areas, and the results of these actions should be measurable. According to the EEA [8], to support the new goals of circular economy, a reliable and responsive monitoring system is needed at all levels, from EU-wide statistics to sectoral datasets.

Although the comprehensive assessment of the circular economy in the EU remains an actual problem, there are empirical studies, which focus on assessing the progress in the area of circular economy in the EU Member States. Škrinjaric [9] uses the Gray Relational Analysis as a nonparametric approach of constructing a ranking system between different alternatives, and discloses regional discrepancies within the EU. The estimates are based on the official statistical data provided by *Eurostat* and categorized as Circular Economy Indicators. Although this category includes only several variables which can be compared over time and countries, the results of the research reveal at least the relative effectiveness of the selected European countries in terms of achieving circular economy goals. Germany, the Netherlands, Denmark, France, and Italy are recognized as best performing countries, while Romania, Greece, Cyprus, Slovakia, and Bulgaria are indicated as worst performing ones. The author discusses that the progress of the leading countries in the field of circular economy can be determined by their higher degree of economic development (measured as GDP per capita), better infrastructure, more efficient education systems, and the development of R&D. Meanwhile, the countries with the lowest ratings are characterized by a higher level of corruption, lower government efficiency indices, and lower State of Learning and Equity in Education (PISA) results.

Nazarko et al. [10] combine the Data Envelopment Analysis, which allows for studying the relative efficiency of decision-making units; they also use factor analysis and cluster analysis. The authors select 27 EU Member States and 16 indicators for their analysis. Their factor analysis showed that many indicators of circular economy are strongly correlated, and thus can be aggregated into five meta-indicator groups: recycling rate of general waste, recycling rate of special waste, waste production, circular material use rate, and jobs and investments. The research did not reveal any obvious leader in the area of the circular economy in the EU, but it disclosed the leaders with respect to particular indicators: Germany was found to be a leader in recycling municipal waste, Slovenia—in recycling all waste excluding major mineral waste, Belgium—in recycling overall packaging and wooden packaging, Lithuania—in recycling plastic packaging, Croatia—in recycling e-waste, and Austria—in recycling biowaste. No pioneers were identified in the recovery rate of construction and demolition waste. Romania was found to generate the largest amounts of municipal waste per capita and waste excluding major mineral waste per domestic material consumption. The Netherlands was recognized as most advanced in circular material use, Slovakia has the largest gross investment in tangible goods as percentage of GDP, Lithuania and Latvia have the greatest number of persons employed in their circular economy sectors as percentage of total employment, Croatia generates the highest value added at factor cost, while Luxemburg issues the greatest number of patents related to recycling and secondary raw materials. The results imply that the position of a particular country in achieving the goals of circular economy is strongly correlated with its GDP per capita, i.e. richer economies are more advanced in achieving the aims of circular economy because the implementation of these goals requires investments and costs that less advanced economies can hardly bear.

Ūsas et al. [11] propose the indicator system, which covers input use (circularity), trade flows, and recycling processes. They find Germany, Sweden, and the Netherlands to be the most advanced EU Member States in terms of the circular economy development. Their empirical research also implies that the water-locked and the new EU Member States tend to have lower rates of circularity, which could be increased through closer monitoring of the flows of waste and the development of recycling facilities. The authors propose that after implementing the last two conditions, circularity can be improved regardless of the level of the national economic development.

Fura et al. [12] use the multidimensional comparative analysis, in particular, a zero unitarization method, to research the level of advancement in 28 EU Member States in the years 2010, 2012, 2014, and 2016. They use the variables representing the four areas of circular economy (production and consumption, waste management, secondary raw materials, and competitiveness and innovation), provided by *Eurostat*. The authors find that the highly economically developed Benelux countries (Luxembourg, the Netherlands, and Belgium) are most advanced in the area of circular economy, while Malta, Cyprus, Estonia, and Greece are the least advanced in this area within the EU-28. The authors also highlight the

significant disproportions between the "new" EU Member States in terms of their progress in circular economy. These disproportions are observed in each of the four circular economy areas and are related to the specificity of individual countries, although the gradual alignment of the circular economy development levels is also noted. The "new" EU Member States are recommended to focus on competitiveness and innovation, develop safety technologies, and transform their production and consumption patterns.

Marques and Teixeira [13] used Data Envelopment Analysis of the indicators provided in the EU's circular economy monitoring framework, and employed the Fractional Regression Models to measure the progress of the EU Member States in achieving circular economy goals, especially in the field of waste management. They researched 24 EU Member States in the period 2011–2019. The results revealed that the progress of the EU countries is not homogeneous, and a gap between the northern and southern countries can be observed. The Netherlands was found to be the highest scoring country, while Bulgaria, Ireland, and Romania exhibited a downward trend during the period under consideration. The Fractional Regression analysis suggests that the circular economy policies in the EU Member States should concentrate on environmental awareness through education, enhancing the Human Development Index, promotion of circular economy in the areas with greater urban population, and decoupling economic growth from environmental damage.

D'Adamo et al. [14] assess the effect of 15 circular economy indicators, provided by *Eurostat*, and the performance of 27 EU Member States in the period 2019–2020. The results of the Analytic Hierarchy show that the indicators in the category 'Competitiveness and Innovation', which along with the indicators in the category 'Global Sustainability and Resilience' account for two thirds of the overall weight, have the greatest effect on the progress of circular economy. The multi-criteria decision analysis implies that the western European countries are more advanced in the field of circular economy than the eastern European countries. Belgium is indicated as the EU leader by the baseline and alternative scenarios; Italy, France, and Latvia lead by the baseline scenario; Italy, and the Netherlands lead by the alternative scenario. The authors also find that illegal waste management, lack of knowledge and low level of investment in circular technologies, as well as low distribution of value among stakeholders are the major barriers which impede the development of circular economy within the EU.

The United Nations (UN) Economic Commission for Europe [15] provides the major principles, which must be followed to select the indicators for monitoring circular economy. These principles include the significance and usefulness of policies for consumers, analytical reliability, and measurability. The UN Economic Commission for Europe [15] notes that the indicators, which best reflect the main trends of the transition to circular economy, must be carefully selected, as the number of potentially useful indicators can be large, and it is necessary to apply the commonly agreed ones, which would validate their selection. Mazur-Wierzbicka [16] conducted the analysis of the available circular economy indicators used in the EU, and assessed them in terms of usefulness, reliability, acceptability, and soundness. The author concluded that the indicators employed in the European Commission's Circular Economy Monitoring Framework are consistent with the European Commission's goals declared in the fundamental EU documents, and thus far they have been the only framework for monitoring circular economy.

The EEA [8] indicates that the Circular Economy Monitoring Framework (CEMF), initiated by the European Commission in 2018, is a reliable, freely available, and quality-assuring circular economy monitoring system. To more accurately reflect the issues of circular economy, the system was supplemented with some new indicators in 2023. The indicators are provided in Table 1.

Table 1 shows that each criterion of circular economy is assessed by employing the corresponding indicators, the positive/negative change of which reflects the progress/failure of circular economy. According to the EEA [8], the new monitoring framework represents a broader approach to circular economy, with consideration not only of waste recycling, but also of the economic production, the footprint of materials, consumption, the global aspects of sustainability, neutrality, and resilience. Nevertheless, the analysis of single indicators allows for assessing the dynamics of circular economy in the period under consideration or for comparing particular criteria by the change in a specific indicator. This study uses the circular economy indicators, proposed in the CEMF, and expands previous studies by employing a wider set of methods, including the Entropy and expert evaluation for estimating criteria weights, and the PROMETHEE, SAW and TOPSIS methods for multi-criteria decision analysis.

Table 1 The circular economy monitoring framework. Source: adapted by the authors from the European Commission [26]

Area	Validity	Indicators
Production and consumption	Decreasing consumption of materials means that economic growth is decoupled from the use of resources	• Resource productivity • Consumption of raw materials • Green public procurement
Waste generation	In a circular economy, the generation of waste is reduced to a minimum	• Total amount of generated waste per inhabitant • The ratio of the total amount of generated waste (excluding large mineral waste) to GDP • Amount of generated municipal waste per inhabitant • Food waste • Amount of packaging waste per inhabitant • Amount of plastic packaging waste per inhabitant
Waste management	Improved recycling is part of the transition to a circular economy	• Municipal waste recycling rate • The rate of recycling of all waste, except for large mineral waste • Waste recycling rate for all packaging • Plastic packaging waste recycling rate • Recycling rate for separately collected electrical and electronic equipment waste
Secondary raw materials	In a circular economy, secondary raw materials are usually used to make new products	• Circular use of materials • Proportion of materials that are recycled at the end of the life cycle
Trade in recyclable raw materials	Trade in recyclable raw materials shows the importance of the internal market and participation in circular economy at the global level	• Import from non-EU countries • Export to non-EU countries • Internal EU trade
Competitiveness and innovation	A circular economy can help create jobs and boost economic growth	• Private investment • Employment
Green innovation	Innovative technologies, related to circular economy, tend to increase the EU's global competitiveness	• Patents related to waste management and recycling
Global sustainability	Circular economy helps ensure climate neutrality	• GHG emissions during production activities • Usage footprint
Resilience	Circular economy contributes to the security of the supply of raw materials and helps reduce the risks associated with supply disruptions, especially of the critical raw materials	• Dependence on the import of raw materials • The EU supply of raw materials (%)

3 Methodology for assessing the circular economy indicators

The Entropy and expert evaluation methods were used for estimating criteria weights. The Entropy method is one of the most common methods for estimating the weights of different criteria. According to Qu et al. [17], the method is widely used in comprehensive assessment studies which consider different indices. Podvezko and Podviezko [18] note that an increase in the Entropy weight is linked to the degree of dominance of the value of one criterion among all alternatives, and though multiple regression models and other methods can also be applied to this type of research, the objective method of Entropy is the most common method for estimating objective weights in practice [18]. This research follows the steps of the Entrophy method, provided by Jin et al. [19]: (1) matrix values are normalised by applying the relevant formulas, depending on the direction (maximisation or minimisation); (2) the information utility value (variation level, non-normalised values of the Entropy weights), as well as criterion weights are estimated for each indicator.

The expert evaluation contributed to ranking the EU Member States by their progress in circular economy. According to Tidikis [20], expert evaluation is widely used in sociological research to obtain empirical data in the field under consideration. To understand what significance circular economy experts attribute to the selected criteria, the method of expert evaluation (a questionnaire survey) was used. Tidikis [20] notes that the reliability of expert evaluation depends on the selection of experts. The persons selected as experts must be competent, have special experience and know the field directly related to the object of expertise [20]. To ensure the reliability of the method, the persons with professional experience in the field of circular economy, who have been working in this field for at least 3 years [scientists from foreign countries, analysts studying circular economy at the national level, representatives of government institutions (Innovation Agency, Green TecHub, Ministry of Economy and Innovation of the Republic of Lithuania)] and who have the experience of previous participation in similar research, were invited as experts. The survey involved 11 experts. To evaluate the compatibility of the expert opinions, Kendall's coefficient of concordance (W) was used. If the opinions of the experts were compatible, the value of the coefficient of concordance (W) was close to 1; if the opinions were very different, the value of W was close to 0 [21].

Multi-criteria evaluation, based on the PROMETHEE, SAW and TOPSIS methods, is designed to support decision-making when several alternatives need to be assessed by considering many criteria. In this case, the methods indicate the progress of the circular economy indicators in the EU Member States.

Scholars note that the uniqueness of the PROMETHEE method is its deeper logic, and the method itself belongs to the category of complex multi-criteria methods: it indirectly combines the values of the applied criteria (and their weights), and transforms them through priority functions [22]. The literature analysis by Remeikienė et al. [23] implies that the PROMETHEE method is one of the most common MCDA methods. Its main advantages are that the method is simple in terms of the concept and calculation and is well suited to decision-making issues, which possess a finite set of alternatives to be ranked with consideration of several conflicting criteria [23]. Since the purpose of this research is to empirically assess the progress of the circular economy in the EU Member States, this method will allow to rank the EU Member States by the criteria which affect the level of circular economy.

The Simple Additive Weighing (SAW) method is one of the simplest and most common multi-criteria assessment methods [24]. It represents the main idea of multi-criteria decision analysis: to compile the values of a selected set of criteria into a single cumulative evaluation criterion. The SAW method is implemented by assigning the values of normalised criteria and the significance of their weights to each criterion [25]. By applying the SAW method, the elements of the decision matrix are normalised through linear normalisation formulas, the corresponding members of the normalised decision matrix are multiplied by the significance of the indicators, and the resulting products are summed to estimate the rationality of an alternative. The sum of the products of a rational alternative will be maximal [4].

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is a more advanced method which can be applied to both indicator maximisation and minimisation [25]. The essence of the method is estimation of the distances to the hypothetical best and worst alternatives. An alternative is considered better if its Euclidean distance from the best hypothetical solution is smaller, while the distance to the worst hypothetical solution is greater than that of another worse alternative [22].

The level of the circular economy in the EU Member States will be assessed by including the indicators most common in previous studies and proposed by the European Commission (production and consumption, waste generation, waste management, secondary raw materials, trade in recyclable raw materials, competitiveness and innovation, green innovation, global sustainability, resilience) [26]. The detailed information about the indicators is provided in Table 2.

Table 2 Research indicators. Source: adapted by the authors from the European Commission [26]

Topic	Justification	Indicator	Mark	Unit of measurement
Production and consumption	Represents economic growth decoupled from the use of resources as reflected by declining consumption of materials	Material footprint	MF	tons per capita
		Resource productivity	RP	index
Waste generation	Represents the decrease/increase in waste generation, where decrease means the positive progress and increase—the negative progress in circular economy	Waste generation per capita	WG	kg per capita
Waste management	Represents the amount of waste recycling, where increasing amounts mean the transition towards a circular economy	Waste recycling rate (recycling rate of all waste excluding major mineral waste)	RR	Percent
Secondary raw materials	Represents the development of the secondary raw material market, where the growing use of circular materials means progress in circular economy	Circular material use rate	CMUR	Percent
Trade in recyclable raw materials	Represents trade volumes which reflect the importance of the internal market and participation in circular economy at the global level	Intra EU trade	IINT	tons
Competitiveness and innovation	Represents progress in investment and employment sectors, where circular economy solutions contribute to economic growth	Private Investment (in the circular economy sector)	PI	Percent of GDP, prices
		Persons employed (in the circular economy sector)	PE	Percent of employment
Green innovation	Represents the innovative technologies which tend to increase the EU's global competitiveness	Patents related to waste management and recycling	PA	Number
Global sustainability	Indicates how much the climate impact is reduced/increased, when a decrease means a shift towards climate neutrality	GHG emissions from production activities	GG	kg per capita
Resilience	Represents supply-related risk when a higher percentage means greater dependence on essential raw materials	Material import dependency	MD	Percent

Statistical data have been obtained from Eurostat database/circle economy indicators [33]

A key objective of the circular economy is to reduce the need for new resource extraction by promoting the reuse, recycling, and recovery of materials.

The selected circular economy indicators—Material Footprint (RMC, the indicator was used in Cudečka-Puriņa et al. [27]), resource productivity, waste generation per capita, waste recycling rate, Circular Material Use Rate, intra-EU trade, private investment, Persons employed, Patents related to waste management and recycling, GHG emissions from production activities, Material import dependency—are crucial for monitoring progress toward a sustainable and circular economy. The Material Footprint measures material consumption and highlights how effectively an economy decouples growth from resource use. Resource productivity tracks efficiency in production and consumption. Waste generation and recycling rates assess waste management and resource recovery, indicating the shift toward circular practices. The Circular Material Use Rate evaluates the use of recycled materials, promoting sustainability. Intra-EU trade facilitates the adoption of circular practices across member states, while private investment ensures financial support for scaling circular economy initiatives. Employment in the circular economy sector includes roles in recycling, repair, remanufacturing, sustainable design, and waste management. Tracking employment helps measure the success of circular economy policies in creating new, green jobs, boosting innovation, and fostering economic resilience. Patents related to waste management and recycling represent innovations that improve the efficiency and effectiveness of recycling processes, waste reduction, and material recovery. By promoting practices such as recycling, remanufacturing, and reuse, the circular economy reduces the need for new raw materials, which typically involves energy-intensive extraction and processing, contributing to GHG emissions. By improving recycling rates and encouraging product design for longevity, reuse, and repair, the circular economy helps decrease material import dependency. This shift not only lessens the environmental footprint of material extraction but also enhances economic resilience by reducing exposure to supply chain disruptions. These indicators collectively help gauge the effectiveness of circular economy strategies and identify opportunities for further improvement.

To assess the progress of the circular economy in the Member States, the European Commission [26] provides the indicators which were selected considering their appropriateness, acceptability, reliability, ease and robustness, and which allow for an assessment system based on the official statistic from the *Eurostat* and other official sources without increasing any administrative burden [26]. It is noteworthy that, in order to comprehensively assess the situation of the circular economy in an individual country, a set of the indicators needs to be considered, since each of the indicators can reflect the progress of circular economy in different areas. Thus, this research will cover all the indicators presuming that the level of circular economy is represented by the sum of the products of all indicators and their significances.

Summarising, it can be stated that to assess the situation of circular economy, it is necessary to consider a set of indicators which would reflect the progress in various areas. Production and consumption indicators should reflect the declining use of raw materials, when economic growth is booming despite lower consumption of virgin raw materials. Waste generation and management indicators should reveal minimisation of waste generation and acceptable waste management, based on the waste hierarchy, where prevention, preparation for reuse, and recycling are more desirable operations than disposal or other use of waste. The indicators representing the secondary raw material market should convey the growing use of and trade in secondary raw materials. Competitiveness and innovation, sustainability and resilience indicators should reflect the growth of private investment, the number of patents, employment, the reduction of greenhouse gas emissions, and dependence on raw materials in various sectors of circular economy.

4 Results of the empirical research

4.1 Results of the entropy method

First, the criteria weights were estimated by applying the Entropy method. The values of all the criteria were normalised after identifying whether a criterion is maximising or minimising. The Entropy value, the information utility level and the weights of all indicators were also calculated. The accuracy of the calculations was tested by summing the weights. The criteria weights were assigned to particular indicators by using the PROMETHEE method. The values of the weights are provided in Table 3.

Table 3 indicates that the greatest weights, estimated by applying the Entropy method, were assigned to Patents related to waste management and recycling (0.30952), which is followed by Intra EU trade (0.23899), and Waste

Table 3 Criteria weights by the entropy method. Source: compiled by the authors

CRITERION	WEIGHT
Material footprint (MF)	0.03161
Resource productivity (RP)	0.06836
Waste generation per capita (WG)	0.11531
Waste recycling rate (RR)	0.02804
Circular material use rate (CMUR)	0.08319
Intra EU trade (IIN)	0.23899
Private investment (in the circular economy sector) (PI)	0.03905
Persons employed (in the circular economy sector) (PE)	0.02333
Patents related to waste management and recycling (PA)	0.30952
GHG emissions from production activities (GG)	0.02124
Material import dependency (MD)	0.04136
SUM	1

generation per capita (0.11531). The lowest weights were assigned to GHG emissions from production activities (0.02124), and Persons employed in the circular economy sector (0.02333). The other weights range from 0.005319 to 0.02804. It is noteworthy that all the criteria included in the analysis are significant in assessing the situation of the circular economy in particular countries, but the degree of their significance is different. Therefore, to assess the degree of significance, the objective method of Entropy, where an increase in the Entropy weight is linked to the degree of dominance of one criterion among all alternatives [22] was applied. The estimated weights were further processed by applying the PROMETHEE method, the results of which are presented in the following subsection.

4.2 Results of the PROMETHEE method

The PROMETHEE method was applied for 27 EU Member States. The calculations were based on the latest available statistical data (for 2020). The maximum and minimum values of each criterion, as well as the differences between the maximum and minimum values, are provided in Table 4.

Next, the degree of priority was estimated for each pair of possible solutions, the priority function was applied, and the criterion for comparing two alternatives was derived. This allowed to estimate the positive and negative priorities (φ^+ and φ^+, respectively). The results are provided in Table 5.

Finally, the differences between the positive and negative priorities (φ) were estimated, and the countries were ranked, i.e. the alternatives were arranged in the order of significance, where the highest value of φ represents the best alternative (see Fig. 2).

Table 4 Criteria values by the PROMETHEE method. Source: compiled by the authors

CRITERION	Maximum value	Minimum value	Difference between the maximum and minimum values
Material footprint (MF)	45.487	8.163	37.324
Resource productivity (RP)	4.2887	0.3383	3.9504
Waste generation per capita (WG)	20,993	1483	19,510
Waste recycling rate (RR)	70.3	10.9	59.4
Circular material use rate (CMUR)	27.2	1.5	25.7
Intra EU trade (IIN)	15,965,860	20,856	15,945,004
Private investment (in the circular economy sector) (PI)	1.6	0.2	1.4
Persons employed (in the circular economy sector) (PE)	3	0.4	2.6
Patents related to waste management and recycling (PA)	45.67	0	45.67
GHG emissions from production activities (GG)	13,061.28011	3669.2344	9392.04571
Material import dependency (MD)	90.3	9.1	81.2

Table 5 The positive and negative priorities by the PROMETHEE method. Source: compiled by the authors

Country	φ^+	φ^-
Belgium	6.6845	2.0136
Bulgaria	0.7071	5.7838
Czech Republic	2.3411	2.6934
Denmark	1.7162	3.3263
Germany	14.2823	0.7828
Estonia	1.2638	4.9356
Ireland	2.0322	3.4195
Greece	1.1105	4.2213
Spain	6.0286	1.3155
France	8.1109	0.9094
Croatia	1.6677	3.5846
Italy	7.8144	0.8034
Cyprus	0.9959	4.4728
Latvia	1.7675	3.5082
Lithuania	1.2961	3.9045
Luxembourg	2.8134	4.9894
Hungary	1.6513	3.4378
Malta	1.8050	4.2453
Netherlands	8.1049	1.9420
Austria	3.5612	2.5189
Poland	3.9498	2.3198
Portugal	2.1639	3.0157
Romania	1.2826	4.8053
Slovenia	1.5889	3.3210
Slovakia	1.6286	3.3025
Finland	2.2562	5.9930
Sweden	1.3895	4.4491

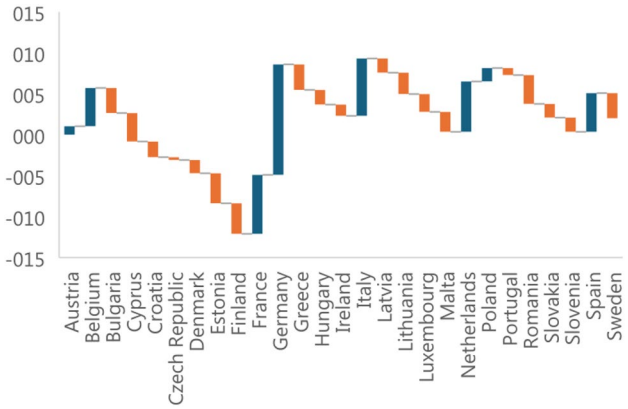


Fig. 2 φ values by the PROMETHEE method, 2020 (Source: compiled by the authors)

The PROMETHEE method, which considered 11 criteria representing the level of circular economy (material footprint, resource productivity, waste generation per capita, waste recycling rate, circular material use rate, intra EU trade, private investment in the circular economy sector, persons employed in the circular economy sector, patents related to waste management and recycling, GHG emissions from production activities, and material import dependency), revealed that the circular economy leaders in the EU are Germany (1), France (2), Italy (3), the Netherlands (4), and Spain (5). The results also indicate that the worst circular economy situation is in Cyprus (23), Romania (24), Estonia (25), Finland (26), and Bulgaria (27).

The same calculations were conducted with the data for 2016 and 2018. The results are provided in Table 6.

Table 6 Country ranks by the PROMETHEE method, 2016–2020. Source: compiled by the authors

Country	2016 rank	2018 rank	Change in 2018 compared to 2016	2020 rank	Change in 2020 compared to 2016
Belgium	5	5	0	6	−1
Bulgaria	26	27	−1	27	−1
Czech Republic	12	11	1	9	3
Denmark	10	10	0	12	−2
Germany	1	1	0	1	0
Estonia	27	26	1	25	2
Ireland	16	18	−2	11	5
Greece	23	23	0	22	1
Spain	6	6	0	5	1
France	2	3	−1	2	0
Croatia	11	14	−3	17	−6
Italy	4	4	0	3	1
Cyprus	22	22	0	23	−1
Latvia	15	17	−2	15	0
Lithuania	17	20	−3	20	−3
Luxembourg	21	19	2	18	3
Hungary	9	9	0	16	−7
Malta	20	21	−1	19	1
Netherlands	3	2	1	4	−1
Austria	8	7	1	8	0
Poland	7	8	−1	7	0
Portugal	13	12	1	10	3
Romania	24	24	0	24	0
Slovenia	14	15	−1	14	0
Slovakia	18	16	2	13	5
Finland	25	25	0	26	−1
Sweden	19	13	6	21	−2

Table 6 shows that the leading position in the area of circular economy in the period 2016–2020 was taken by Germany (rank 1). 10 out of 27 countries (Belgium, Bulgaria, Croatia, Denmark, Cyprus, Lithuania, Hungary, the Netherlands, Finland, and Sweden) recorded the negative change in 2020 compared to 2016. 7 countries (Germany, France, Latvia, Austria, Poland, Romania, and Slovenia) maintained the same results in 2020 compared to 2016, and 10 countries (the Czech Republic, Estonia, Ireland, Greece, Spain, Italy, Luxembourg, Malta, Portugal, and Slovakia) improved their circular economy situation. Ireland and Slovakia recorded the largest positive change, while Hungary and Croatia recorded the largest negative change.

4.3 Results of the expert evaluation

The circular economy experts were involved in the empirical research. They were surveyed through e-mail. The survey was stopped when the required number of responses was collected (11 expert responses) (the recommendation that the number of experts should be equal to the number of criteria under consideration was followed). The experts were asked to rate the significance of the circular economy criteria, with 1 being the highest, and 11—the lowest rank.

To verify the compatibility of the expert opinions, Kendall's coefficient of concordance was estimated, and Pearson's chi-squared test was applied. The value of Kendall's coefficient of concordance was $W = 0.5039$, which means the medium concordance of the expert opinions. The value of Pearson's chi-square test was $X^2 = 55.44$. Since the estimated value was greater than the critical value of the chi-square distribution ($55.44 > 18.37$), with the degree of freedom $v = 11 - 1 = 10$, and significance level $\alpha = 0.05$, it can be stated that the expert opinions are not incompatible.

Table 7 Rearranged criteria values. Source: compiled by the authors

Experts	1	2	3	4	5	6	7	8	9	10	11	SUM
Material footprint (MF)	9	11	1	10	10	10	11	11	9	10	11	103
Resource productivity (RP)	8	8	4	9	4	8	8	7	11	8	8	83
Waste generation per capita (WG)	4	3	3	8	6	4	2	6	3	3	7	49
Waste recycling rate (RR)	5	2	5	7	3	6	3	3	6	2	3	45
Circular material use rate (CMUR)	10	7	2	11	2	7	7	8	7	7	6	74
Intra EU trade (IIN)	1	1	6	3	9	2	1	2	2	1	1	29
Private investment (in the circular economy sector) (PI)	6	6	7	1	1	1	5	1	1	6	2	37
Persons employed (in the circular economy sector) (PE)	2	4	10	4	11	3	4	5	4	5	4	56
Patents related to waste management and recycling (PA)	3	10	11	5	8	11	9	10	10	11	10	98
GHG emissions from production activities (GG)	7	5	9	2	5	5	6	4	5	4	5	57
Material import dependency (MD)	11	9	8	6	7	9	10	9	8	9	9	95
SUM	66	66	66	66	66	66	66	66	66	66	66	726

Table 8 Criteria weights by the expert evaluation. Source: compiled by the authors

CRITERION	WEIGHT
Material footprint (MF)	0.141873
Resource productivity (RP)	0.114325
Waste generation per capita (WG)	0.067493
Waste recycling rate (RR)	0.061983
Circular material use rate (CMUR)	0.101928
Intra EU trade (IIN)	0.039945
Private investment (in the circular economy sector) (PI)	0.050964
Persons employed (in the circular economy sector) (PE)	0.077135
Patents related to waste management and recycling (PA)	0.134986
GHG emissions from production activities (GG)	0.078512
Material import dependency (MD)	0.130854
SUM	1

The expert evaluations allowed to estimate the weights for each criterion. First, the evaluation matrix was rearranged by applying the method of linear transformation, and the sum of ranks was calculated for each indicator (see Table 7).

Next, the weights of each indicator were estimated, and the sum of the weights was verified to be equal to 1. The weights are provided in Table 8.

The estimations, based on the expert evaluations, indicate that the greatest weights are assigned to Material footprint (0.141873), Patents related to waste management and recycling (0.134986), and Material import dependency (0.130854), while the lowest weights are assigned to Intra EU trade (0.039945), and Private investment in the circular economy sector (0.050964).

The estimated weights were inserted into the circular economy evaluation formula, which will be used in the SAW and TOPSIS methods:

CE = 0.141873MF + 0.114325RP + 0.067403WG + 0.061983RR + 0.101928CMUR + 0.039945IINT + 0.050964PI + 0.077135PE + 0.0134986PA + 0.078512GG + 0.130854MD.

4.4 Results of the SAW and TOPIS methods

When applying the SAW method, the criteria were first normalised. Then the normalised values of each criterion were multiplied by the significance weights. Values S_j of the generalised criterion SAW, as well as the country ranks, are provided in Fig. 3.

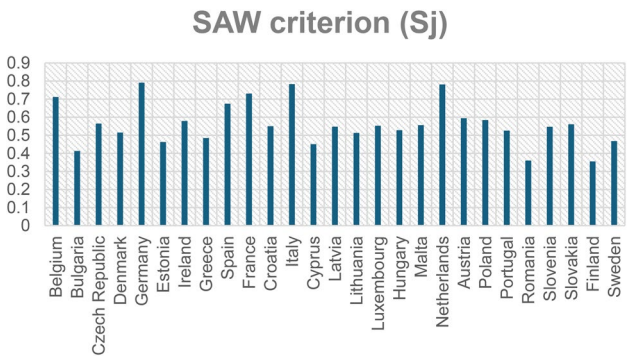


Fig. 3 SAW criterion values (Source: compiled by the authors)

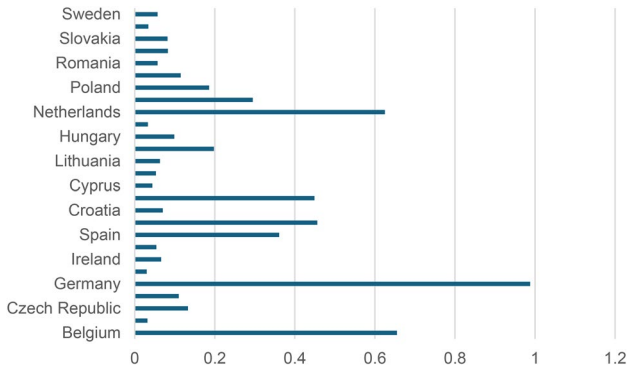


Fig. 4 C_j^* values by the TOPSIS method (Source: compiled by the authors)

The SAW estimations show that the best circular economy situation with consideration of the 11 indicators is in Germany (1), Italy (2), and the Netherlands (3), while the worst situation is in Bulgaria (25), Romania (26), and Finland (27).

When applying the TOPSIS method, the criteria were first normalised. Then the normalised values of each criterion were multiplied by the significance weights, and the best and worst alternatives, as well as the Euclidean distance to the best and worst hypothetical solutions, were estimated. Finally, values C_j^* of the TOPSIS criterion and the country ranks were estimated (see Fig. 4).

The TOPSIS estimations show that the best circular economy situation with consideration of the 11 indicators is in Germany (1), Belgium (2), and the Netherlands (3), while the worst situation is in Malta (25), Bulgaria (26), and Estonia (27).

4.5 Comparison of the research results

This subsection compares the results of the empirical research obtained by applying different methods. The summary of the results is provided in Table 9.

When different multi-criteria decision-making methods are used, but the same criteria are considered, the results are not necessarily the same since in addition to reliability, each method has its internal logic which affects final results. Ginevičius and Podvezko [25] provide a solution to generalise the results. According to the authors, the most relevant and simplest way is selection of indicators for a certain criterion, and the most elementary criterion in this case is the strength of the correlation between various multi-criteria evaluation methods; if the correlation is close to 1, then the data can be united into a single package [25]. Since the Spearman correlation between the SAW and other methods was statistically significant ($p < 0.05$) and close to 1, the results were united into a single package (see Table 9).

The Spearman correlation between PROMETHEE and SAW is very high (0.93), indicating that the rankings from these two methods are nearly identical. The correlation between TOPSIS and SAW is also quite strong (0.835), though not as high as between PROMETHEE and SAW, suggesting that there is still some difference in the rankings produced by TOPSIS, but they are generally in line with the other methods.

Table 9 Comparison of the research results (country ranks). Source: compiled by the authors

Country	PROMETHEE	SAW	TOPSIS	Generalised rank
Belgium	6	5	2	4
Bulgaria	27	25	26	26
Czech Republic	9	10	10	10
Denmark	12	19	12	14
Germany	1	1	1	1
Estonia	25	23	27	25
Ireland	11	9	17	12
Greece	22	21	21	21
Spain	5	6	6	6
France	2	4	4	3
Croatia	17	14	16	16
Italy	3	2	5	3
Cyprus	23	24	23	23
Latvia	15	15	22	17
Lithuania	20	20	18	19
Luxembourg	18	13	8	13
Hungary	16	17	13	15
Malta	19	12	25	19
Netherlands	4	3	3	3
Austria	8	7	7	7
Poland	7	8	9	8
Portugal	10	18	11	13
Romania	24	26	20	23
Slovenia	14	16	14	15
Slovakia	13	11	15	13
Finland	26	27	24	26
Sweden	21	22	19	21
Correlation coefficient (Spearman)	0.92796093	1	0.83516484	

Overall, 9 table suggests that PROMETHEE and SAW are highly aligned, while TOPSIS presents some variation, though still consistent enough to generate similar conclusions for most countries. The generalized rank can be seen as a reliable measure that accounts for these slight discrepancies between methods.

- **Germany** consistently ranks highest across all methods (rank 1), suggesting it performs best according to the criteria measured.
- **Finland** ranks lowest across all methods, indicating it is less competitive in the context being measured.
- Countries like **Belgium**, **France**, and **Italy** have relatively high rankings across all methods, with small differences between the individual method rankings.
- **Estonia**, **Cyprus**, and **Romania** show more variation between the methods, reflecting the differing weightings and perspectives the methods apply in their analysis.

Summarising, the results of the empirical research suggest that the top EU Member States with the highest level of circular economy are Germany (1), France, Italy, the Netherlands (2–4), and Belgium (5). The lowest level of circular economy is observed in Cyprus, Romania, Estonia, Finland, and Bulgaria. Unfortunately, the development of the circular economy in EU countries is not comprehensive; overall, their economy is still linear [28].

5 Discussion

In recent years, we can see digital transformation, increasing globalization processes, more accessible access to resources and services globally [29]. Scientific literature is characterised by a variety of circular economy concepts since a circular economy can be assessed from various perspectives—environmental, social, economic. When analysing the concept of a circular economy, some researchers tend to emphasise the benefits of a circular economy as a closed system, which aims to keep resources in circulation, thus reducing the need for virgin materials and extending a product lifecycle, while others highlight social aspects and the relevance of justice, cooperation, education, and involvement, or state that circular economy is inseparable from environmental protection and is the basis for solving environmental problems. To identify the criteria which represent circular economy and allow to conduct the multi-criteria analysis of the circular economy situation in different countries, this research is based on a broad concept of circular economy, which considers its multi-sidedness and influence in different (economic, social, and environmental) areas. The scientific literature analysis proves that a comprehensive assessment of the circular economy situation in different countries calls for a complex approach and consideration of the areas, which are critically affected by the circular economy models, in particular, production and consumption, waste generation, waste management, functioning of the secondary raw material markets, competitive environment with innovation and innovative solutions, global sustainability, and resilience.

The systematic review provides an overview of existing indicators and measurement tools at the organisational level [30], therefore, for the analysis at the country level, officially available statistical data from Eurostat were chosen.

The results of the empirical research are in line with the findings provided by previous studies, which show the discrepancies within the EU regarding the progress in circular economy [9, 12, 13]. This research reflects the same tendency, showing that "old" and more economically advanced EU Member States demonstrate faster development of their circular economies compared to "new" and less economically developed countries [12], which can allocate less funds for investment in recycling facilities [11], innovation, transformation of production and consumption patterns [12], and building the relevant infrastructures [9]. As in previous studies [9, 11, 12], this empirical research identified Germany, France, Italy, and the Netherlands as the leaders in the area of circular economy in the EU, although Nazarko et al. [10] note that no clear leader can be identified, and it is only possible to identify the leaders in relation to particular circular economy indicators.

Germany, France, Italy, the Netherlands, and Belgium are leaders in the EU's circular economy due to the following best practice examples [31]:

1. *Germany* has implemented Extended Producer Responsibility (EPR), which allowed manufacturers to take responsibility for their products' lifecycle. The Circular Economy Act (KrWG) promotes recycling and waste reduction, supported by an efficient waste sorting and recycling infrastructure, including energy recovery.
2. *France* passed the Circular Economy Law (*Loi Anti-Gaspillage pour une Economie Circulaire*) in 2020, setting long-term goals for reducing plastic waste, banning single-use products by 2040, and requiring electronic devices to be repairable. It mandates increased recycling rates and the use of secondary raw materials by manufacturers.
3. *Italy* has established the National Waste Prevention Program (PNPR), focusing on industrial symbiosis, especially in northern regions, where waste from one industry is utilized as resources in another. The "End of Waste" decrees facilitate the use of secondary raw materials in industries, including plastics and paper.
4. *The Netherlands* has adopted a Circular Economy Action Plan aimed at achieving a fully circular economy by 2050 and reducing the use of resources by 50% by 2030. The country promotes material recycling and the use of secondary raw materials in industries, particularly in construction and agriculture.
5. *Belgium* leads the circular economy through its regional strategy, the Flanders Circular Economy Plan, which aims to reduce waste and promote recycling. The strategic document "Visie 2050" seeks to fully integrate the country's circular economy by 2050, and emphasizes resource efficiency, recycling, and the use of secondary raw materials across sectors. Additionally, industrial symbiosis models are well-established, which allows industries to use each other's waste as resources.

Cyprus, Romania, Estonia, Finland, and Bulgaria have less developed circular economies due to various barriers. For instance, Cyprus and Bulgaria face infrastructure deficiencies and a high reliance on landfills, which results in limited recycling capabilities. Romania struggles with low awareness among citizens and businesses, along with underdeveloped waste management systems. According to Gorgon et al. [32] quantitative analysis results of the social economy and transition towards a circular economy in Romania more than half of the surveyed enterprises did not understand

the concept of a circular economy. Estonia lacks comprehensive circular economy policies, still relying on traditional waste management models, dominated by landfills. Finland, despite the progress achieved, is still facing the challenges in expanding circular economy innovations beyond the niche sectors, like biotechnology, environmental design, and construction [31].

6 Conclusions

The objectives of circular economy, which include proper waste management as the maturity feature reflecting the aims of a long-term policy, alongside other aspects, such as value retention and production, innovations, prevention of climate change and pollution problems, and development of the secondary raw materials markets, suggest that a comprehensive analysis must cover the relevant indicators to represent the situation in the key areas. This research covers the following indicators: material footprint, resource productivity, waste generation and recycling rates, circular material use rate, intra EU trade, private investment, persons employed in the circular economy sector, patents related to waste management and recycling, GHG emissions from production activities, and material import dependency. The methods selected for this research include literature analysis, systematisation and summarisation, secondary data analysis, statistical data analysis, expert evaluation, the Entropy method for estimating criteria weights, and the multi-criteria decision analysis based on the PROMETHEE, SAW, and TOPSIS methods.

The empirical research revealed that the major criteria for assessing the level of the circular economy in the EU, according to the experts, are material footprint (significance rate of 0.141873), patents related to waste management and recycling (significance rate of 0.134986), and material import dependency (significance rate of 0.130854). The experts consider intra EU trade (significance rate of 0.039945), and private investment in the circular economy sector (significance rate of 0.050964) the least important criteria. The results of the SAW method revealed that Germany ranks first in terms of the circular economy situation. It is followed by Italy and the Netherlands, while the worst situation is in Bulgaria, Romania, and Finland. The TOPSIS method confirmed the leading position of Germany, which is followed by Belgium and the Netherlands, while Malta, Bulgaria and Estonia have the lowest ranks. By applying the Entropy method, the highest weights were estimated for the following criteria: patents related to waste management and recycling (0.30952), intra EU trade (0.23899), and waste generation per capita (0.11531); the lowest weights were estimated for GHG emissions from production activities (0.02124), and persons employed in the circular economy sector (0.02333). The PROMETHEE method ranked Germany as the leading country, followed by France and the Netherlands, while Finland, Bulgaria, and Estonia had the lowest ranks. Since the Spearman correlation between the SAW and other methods was statistically significant and close to 1, the results were united into a single package, which indicates that the top EU Member States with the highest level of the circular economy are Germany (1), France, Italy, the Netherlands (2–4), and Belgium (5). The lowest level of the circular economy is observed in Cyprus, Romania, Estonia, Finland, and Bulgaria.

Considering the literature analysis and the results of the empirical research, the following recommendations can be provided:

1. To promote the development of circular economy, not only proper waste management, but also the use of innovative business models, based on advanced technologies and decisive solutions, must be considered at the stage of product development. For instance, eco-design can raise the proportion of easily recyclable materials in production, reduce the variety of material types, incorporate well-compatible, renewable and natural materials, prevent or reduce the use of toxic and harmful materials. Also, each product must have clear recycling instructions and material identification labels, while eco-design should focus on reducing waste throughout a product's life cycle.
2. To develop innovative circular solutions, business companies, governmental agencies, NGOs, and academic communities must strengthen cooperation and share the knowledge, resources, and best practices. As leaders in circular economy, Germany, France, Italy, the Netherlands, and Belgium should share their good practices that could be adopted by other EU Member States. For instance, Germany's approach to circular economy covers the regulatory framework, incentives, and public awareness efforts. The country constantly invests in scientific research, promotes green procurement practices, enforces extended producer responsibility laws, by which manufacturers must take responsibility for the entire life cycle of their products, including collection, recycling, and disposal.
3. The major indicators of circular economy must be regularly updated in the portals of official statistics (such as *Eurostat*) since the latest data are needed for reliable research. The data for 2022, and in some cases—for 2020 were

only available for this research, which impeded the research development and analysis. The official statistics could be supplemented with generalised country ranks, which would represent the sum of the significances of all circular economy indicators and the products of their values. The ranks would allow for a simple and easily accessible multi-criteria evaluation for all stakeholders.

The authors of this article note that the most challenging aspect when conducting the empirical research was to find experts in a circular economy. Additionally, the subjective nature of expert evaluations may have led to differing indicator weights. If similar research were conducted in other countries, it would be important to check whether the results could differ. There was also a lack of the statistical data regarding circular economy indicators.

Future research could focus on the effectiveness of implementing circular economy plans and strategies in the EU Member States. Such studies could include survey results and focus group data, analyse how different/similar the Member States are in achieving their goals, which policy measures are most/least effective, and how best practices can be more widely applied. Additionally, it would be useful to examine the challenges and success examples to ensure a sustainable transition to a circular economy.

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Author contributions R.R wrote the theoretical part of the paper and prepared manuscript according the journal requirements. She wrote the conclusions and recommendations. L.G. selected the methodology and made the calculations. J.B. was responsible for the statistical data analysis and description of the research results.

Data availability The datasets generated during the current study are available from the corresponding author on reasonable request. The data sources are available from publicly accessible EU circular economy datasets, and any additional calculations or supplementary files used during the study will be accessible via (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Circular_economy_-_material_flows) upon publication. These materials will include detailed statistical data, calculations, and relevant links, ensuring transparency and enabling further research based on our findings.

Declarations

Ethics approval and consent to participate The research was carried out following the guidelines of the ethics committee listed in the ethics statement. The protocol was approved by Vytautas Magnus University Ethical Committee in accordance with the Code of Ethics and Regulations of the Ethics Committee. The informed consent to participate was obtained from all the participants.

Competing interests The authors declare no competing interests.

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