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MULTI-CRITERIA DECISION ANALYSIS OF CIRCULAR ECONOMY PERFORMANCE IN THE BALTIC STATES: A COMPARATIVE EVALUATION

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Abstract. This study embarks on a comparative evaluation of Circular Economy (CE) performance in the Baltic States (Latvia, Lithuania, and Estonia) using a robust multi-criteria decision-making (MCDM) framework. Drawing on 22 key indicators, the research applies the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to systematically rank the country-level CE implementation across five thematic dimensions: production and consumption, waste management, secondary raw materials, competitiveness and innovation, and global sustainability. The results reveal that Latvia ranks highest, followed by Lithuania and Estonia, underscoring significant differences in waste management efficiency, investment in CE sectors, and material self-sufficiency. The main contribution of this paper lies in the development of a comprehensive, quantitative benchmarking framework that integrates multiple CE indicators and MCDM methods to assess national performance in a data-driven manner. The methodology developed here can serve as a replicable model for CE assessment in other regional or national contexts.

Keywords: Circular Economy, Baltic States, EUROSTAT, MCDM, TOPSIS, sustainability indicators.

JEL Classification: M11, M14, M21, C44, C61.

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1. Introduction

The Circular Economy (CE) has emerged as a fundamental approach to achieving sustainable development by promoting efficient resource utilization, waste minimization, and the increased adoption of recycling and reuse strategies (Mohammed et al., 2021). Within the European Union (EU), the transition to a CE is strongly encouraged through regulatory frameworks such as the Circular Economy Action Plan (CEAP), which aims to reduce environmental impact while fostering economic growth through circular business models (Chioatto & Sospiro, 2023). However, despite a unified EU strategy, the implementation of CE principles varies across member states due to differences in economic structures, industrial composition, waste management systems, and policy effectiveness. The Baltic states Lithuania, Latvia, and Estonia each face distinct challenges and opportunities in advancing their Circular Economy efforts. A comparative assessment of their CE performance is essential to identify key sustainability trends, strengths, and areas that require policy intervention (Alberich et al., 2023).

The EU CEAP provides a structured roadmap for countries to transition towards sustainable production and consumption systems by enhancing resource efficiency, reducing waste generation, and increasing the utilization of secondary raw materials. Despite their geographical proximity and shared EU policy commitments, Lithuania, Latvia, and Estonia exhibit differing levels of CE implementation due to factors such as economic priorities, industrial dependency, technological readiness, and public awareness (Chioatto & Sospiro, 2023). Estonia has made significant progress in integrating digital solutions and eco-innovation into its CE transition, while Lithuania and Latvia continue to face challenges in waste management efficiency and material recovery rates. Understanding the underlying reasons for these disparities is crucial for designing targeted policy measures that can bridge the gaps and enhance circular economic performance across the region (Wang et al., 2025).

Although EU policies provide a common framework for CE development, significant differences exist in actual CE performance among the Baltic states. These disparities stem from variations in waste management infrastructure, recycling capacity, resource productivity, investment levels in CE sectors, and policy enforcement mechanisms (Grybaitė & Burinskienė, 2024; Strapchuk et al., 2025). Consequently, CE progress has been uneven, creating challenges in aligning national efforts with EU sustainability targets. Furthermore, while multiple CE indicators exist, there is no comprehensive ranking system that systematically evaluates and compares CE implementation among Lithuania, Latvia, and Estonia. Without such a structured ranking, it remains difficult to determine which country leads in CE adoption and what specific areas require further attention (Mazur-Wierzbicka, 2021).

To address this gap, this study aims to assess and compare the Circular Economy performance of Lithuania, Latvia, and Estonia using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a Multi-Criteria Decision-Making (MCDM) approach. TOPSIS is employed to rank these countries based on key CE indicators, including material footprint, resource productivity, recycling rates, waste generation per capita, and secondary raw material use. The primary objective is to establish a systematic and objective ranking that highlights national strengths, weaknesses, and policy gaps, thereby offering valuable insights to policymakers and sustainability experts.

This research is important for several reasons. First, it contributes to the growing body of literature on CE performance evaluation by applying a quantitative decision-making method to rank countries based on sustainability indicators. Second, the use of TOPSIS ensures an objective and data-driven approach, minimizing potential biases in the ranking process. Third, the study's findings will provide valuable insights for policymakers, helping them identify priority areas for CE development and optimize resource management strategies. By understanding which country excels in specific CE aspects, decision-makers can design targeted interventions that enhance sustainability outcomes across the Baltic region.

While numerous studies have examined CE performance using single indicators or conventional ranking approaches, few have developed a comprehensive multi-indicator framework combined with methodological validation. The innovation of this study lies not merely in the use of TOPSIS, but in its integration with 22 Eurostat-based CE indicators and its triangulation with MABAC and COPRAS methods for robustness testing. This approach ensures consistency and reliability in country rankings and enables policymakers to make data-informed strategic interventions.

This study assesses CE performance based on five key categories of indicators: (1) Production and Consumption, covering material footprint and resource productivity; (2) Waste Management, focusing on recycling rates and waste generation; (3) Secondary Raw Materials, measuring circular material use and trade in recyclable materials; (4) Competitiveness and Innovation, assessing investment in CE sectors and employment in circular industries; and (5) Global Sustainability and Resilience, evaluating environmental impacts such as greenhouse gas emissions and material self-sufficiency. These indicators provide a holistic and data-driven assessment of CE progress in the Baltic states.

The study's results are expected to yield a clear ranking of Lithuania, Latvia, and Estonia in terms of their CE performance, identifying which country is leading in sustainability and which areas require policy improvement. By employing TOPSIS, the study ensures that the ranking is scientifically structured and reflective of each country's CE performance. Additionally, by analyzing CE performance through multiple sustainability dimensions, this research will provide deeper insights into how policy, economic investment, and technological advancements influence Circular Economy progress.

The findings of this research will be particularly valuable for policymakers, environmental agencies, and industry stakeholders in the Baltic region. By identifying best practices and weaknesses in CE performance, the study can support the development of targeted policies that improve resource efficiency, enhance waste management systems, and foster a more sustainable economic model. Furthermore, the ranking system established in this study can serve as a benchmarking tool for future CE assessments, enabling continuous monitoring and policy adjustments to support long-term sustainability objectives.

The transition to a Circular Economy is a key priority for the EU, yet progress among member states remains uneven. Lithuania, Latvia, and Estonia, despite their geographical and economic similarities, exhibit distinct strengths and challenges in CE implementation. This study aims to systematically evaluate and rank their CE performance using the TOPSIS method, ensuring an objective and data-driven assessment. By identifying the best-performing country and highlighting key areas for improvement, this research will support policymakers in refining CE strategies and fostering a more resource-efficient and sustainable Baltic region.

The remainder of this paper is structured as follows. Section 2 reviews the theoretical background of the Circular Economy, discusses relevant performance indicators, and synthesizes prior research applying Multi-Criteria Decision-Making (MCDM) methods in sustainability assessments. Section 3 outlines the research methodology, detailing the indicator selection, data normalization procedures, and the implementation of the TOPSIS model. Section 4 presents the empirical results, including the ranking of CE performance in the Baltic States. Section 5 provides a comprehensive discussion of the findings, highlighting key implications for policymakers and future research directions. Section 6 concludes the paper by summarizing the main contributions, acknowledging limitations, and proposing avenues for further investigation.

2. Literature review

The Circular Economy (CE) represents a paradigm shift from the traditional linear model of production and consumption, which follows a "take-make-dispose" approach, toward a more sustainable system that emphasizes resource efficiency, waste reduction, and material reuse (Rashid & Malik, 2023; Štreimikienė et al., 2024; Streimikis et al., 2024a). This transformation is crucial in addressing global sustainability challenges such as resource depletion, environmental degradation, and climate change. The CE model is particularly relevant in the context of the European Union (EU), where resource efficiency and sustainability are integral to economic policies and environmental regulations (Bathaei et al., 2025; Uddin et al., 2023).

To assess CE performance, a variety of indicators have been developed to measure material consumption, waste generation, recycling rates, and economic efficiency. These indicators provide valuable insights into the effectiveness of CE strategies at the national and regional levels (Barišauskaitė & Mikalauskienė, 2025; Rincón-Moreno et al., 2021). In the EU, Eurostat serves as the primary data source for monitoring CE progress, offering comprehensive statistical frameworks to evaluate production efficiency, waste management, and secondary raw material use. However, despite the availability of these indicators, comparing CE performance across different countries remains a challenge due to variations in economic structures, industrial activities, and policy implementation (Mockus, 2025; Zhang & Dilanchiev, 2022).

The European Union has actively promoted the Circular Economy as a key component of its sustainability strategy through initiatives such as the Circular Economy Action Plan (CEAP) (Chioatto & Sospiro, 2023; Streimikis, 2025). First introduced in 2015 and later updated in 2020, CEAP sets ambitious targets for waste reduction, material efficiency, and the transition toward a climate-neutral economy (Alevizos et al., 2023; Streimikienė & Bathaei, 2025). These goals align with the broader objectives of the European Green Deal, which aims to achieve carbon neutrality by 2050 while fostering sustainable economic growth. Under CEAP, EU member states are required to implement national policies that promote circularity in production and consumption, improve waste management, and enhance the role of secondary raw materials in the economy (Bathaei & Štreimikienė, 2023b; Karpavicius & Balezentis, 2025; Reis et al., 2023).

Despite being part of the same regulatory framework, EU member states have demonstrated varying levels of success in CE implementation (Rizos & Bryhn, 2022). Countries such as the Netherlands, Germany, and Sweden have made substantial progress in circularity by integrating innovative waste management systems and promoting eco-design principles (Krisciukaitiene & Bathaei, 2025; Melles et al., 2022). However, Eastern and Baltic European countries, including Lithuania, Latvia, and Estonia, have faced challenges in meeting CE targets due to differences in infrastructure, economic policies, and industrial composition (Nowak et al., 2023).

Among the Baltic states, Estonia has emerged as a leader in digital and technological innovations that support CE initiatives, such as smart waste collection and automated sorting systems (Ūsas et al., 2025). However, the country still struggles with improving its recycling rates and reducing waste generation per capita. In contrast, Latvia and Lithuania have lower levels of CE integration, with significant challenges in waste collection efficiency and resource recovery (Hoang et al., 2022). While both countries have made progress in reducing landfill dependency, they still lag in adopting circular production models and increasing material efficiency. Understanding the factors influencing CE performance in these countries is crucial for designing targeted policy interventions and achieving EU sustainability goals (Dey et al., 2022; Streimikis et al., 2024b).

Evaluating and ranking Circular Economy (CE) performance across different nations is a complex task that requires the integration of multiple indicators, each reflecting a specific aspect of sustainability (Candan & Cengiz Toklu, 2022). Since CE performance is influenced by various factors such as waste management efficiency, resource productivity, recycling rates, and material use, a structured approach is needed to systematically compare and rank countries. Traditional assessment methods often focus on individual indicators, failing to provide a holistic evaluation of CE performance (Panchal et al., 2021). To overcome this limitation, Multi-Criteria Decision-Making (MCDM) methods have been increasingly applied in sustainability assessments, enabling a more comprehensive and data-driven analysis (Streimikis et al., 2024a; Yildizbasi & Arioz, 2022).

MCDM techniques are particularly useful for ranking alternatives when multiple, often conflicting, criteria must be considered simultaneously. In the context of CE, these methods allow policymakers and researchers to weigh different indicators based on their importance, helping to identify strengths and weaknesses in national sustainability strategies. Several studies have demonstrated the effectiveness of MCDM approaches in CE-related evaluations (Grybaitė & Burinskienė, 2024; Sousa et al., 2021). For example, Polat et al. (2023) applied MCDM techniques to assess end-of-life recycling input rates (EOL-RIR) across European countries, highlighting the role of secondary raw materials in reducing resource dependency. Their study showed that nations with higher EOL-RIR values exhibit stronger CE integration, as they are more capable of reintroducing materials into economic circulation (Bathaei & Štreimikienė, 2023a; Polat et al., 2023).

Similarly, Rađenović and Rajić (2024) employed TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to rank EU countries based on circular material use rate (cei_srm030). Their findings revealed that countries with well-established waste management infrastructure and strong recycling policies tend to achieve higher circularity rates. TOPSIS, one of the most widely used MCDM methods, ranks alternatives by comparing their distance from an ideal solution, making it a valuable tool for assessing CE performance across multiple indicators (Rađenović & Rajić, 2024).

Given the advantages of each MCDM method, this study integrates TOPSIS to provide a robust and objective ranking of CE performance in the Baltic states. By applying these methods to Eurostat data, the study aims to identify the leading country in CE implementation, as well as highlight areas where improvements are needed (Dey et al., 2022). The combination of multiple MCDM techniques ensures that the ranking is not biased by a single methodological approach, thereby enhancing the reliability and comprehensiveness of the results (Gyani et al., 2022).

The Material Footprint (cei_pc020) quantifies the total raw material used to meet consumption demands, highlighting a country's resource efficiency. Studies such as Lenzen et al. (2022) emphasize that lower material footprints indicate better efficiency in resource utilization and sustainability efforts. On the other hand, resource productivity (cei_pc030) measures economic output per unit of material consumed, typically expressed as GDP per kilogram of material used. Chiang et al. (2024) noted that resource productivity is a key metric in CE assessments, as it reflects the economic benefits derived from efficient material use and lower environmental impact (Chiang et al., 2024).

Waste generation per capita and efficiency in waste management are critical indicators of CE performance. The Waste Generation Per Capita (cei_pc034) metric provides insights into the sustainability of consumption patterns, with studies like Arion et al. (2023) demonstrating how advanced economies achieve lower waste generation through comprehensive policies and circular strategies (Arion et al., 2023). Additionally, the Generation of Waste Excluding Major Mineral Wastes Per GDP Unit (cei_pc032) ensures that waste from industrial and construction activities does not distort the evaluation of CE performance (Bathaei et al., 2019).

Electronic waste, particularly Waste of Electrical and Electronic Equipment (WEEE) Recycling Rate (cei_wm060), is a growing environmental concern due to the increasing disposal of smartphones, computers, and appliances. Rene et al. (2021) found that countries with high WEEE recycling rates successfully recover valuable materials while reducing environmental harm (Rene et al., 2021). Silva et al. (2024) mentioned that the Circular Material Use Rate (cei_srm030) plays a crucial role in CE by indicating the proportion of recycled materials in economic circulation, as highlighted by (Silva et al., 2024).

Indicators related to secondary raw materials are essential for assessing how well a country utilizes recycled materials to reduce dependency on virgin resources. The Contribution of Recycled Materials to Raw Materials Demand (EOL-RIR) (cei_srm010) measures the effectiveness of recycling programs in meeting industrial material needs. Studies such as Topliceanu et al. (2022) emphasize that higher EOL-RIR values indicate successful resource recovery, reducing environmental impact and enhancing material security (Topliceanu et al., 2022). The Trade in Recyclable Raw Materials (cei_srm020) is another important metric that reflects global market dynamics for secondary materials (Gatto, 2023).

Financial investment in Circular Economy sectors is an important driver of sustainability. The Private Investment and Gross Added Value Related to CE Sectors (cei_cie012) measures the financial commitments made toward CE industries, including recycling and remanufacturing. Lehmann et al. (2022) showed that economies investing heavily in CE sectors experience faster sustainability transitions. Moreover, the Persons Employed in Circular Economy Sectors (cei_cie011) indicator highlights the socio-economic benefits of CE adoption, including job creation and skill development in sustainability-oriented industries (Lehmann et al., 2022).

Innovation is a key factor in enhancing Circular Economy practices. The Patents Related to Recycling and Secondary Raw Materials (cei_cie020) indicator tracks the development of new recycling technologies and material recovery processes. Modic et al. (2021) found that countries with a high number of CE-related patents demonstrate strong commitment to research and innovation, driving sustainability advancements (Modic et al., 2021).

The Consumption Footprint (cei_gsr010) provides a holistic assessment of a country's environmental impact based on resource use, emissions, and waste production. Lenzen et al. (2022) emphasized that monitoring consumption footprint is essential for evaluating sustainability progress and ensuring the effectiveness of CE policies (Lenzen et al., 2022).

Greenhouse gas emissions are a major concern in CE evaluations. The Greenhouse Gas Emissions from Production Activities (cei_gsr011) indicator measures emissions generated by industrial and manufacturing processes. Kalpakchiev et al. (2025) found that CE practices such as material efficiency, recycling, and waste reduction significantly contribute to emission reductions, supporting climate change mitigation strategies (Kalpakchiev et al., 2025).

Countries with high material import dependency are more vulnerable to supply chain disruptions and price volatility. The Material Import Dependency (cei_gsr030) indicator assesses the reliance on imported raw materials, with Rai et al. (2021) showing that lower dependency correlates with higher economic resilience and sustainability (Rai et al., 2021).

Although various studies have analyzed individual CE indicators, there is a lack of research that systematically ranks countries based on a combination of CE performance metrics. By using Eurostat data and applying MCDM methods, this study fills an existing gap in sustainability assessments by providing an objective ranking of Lithuania, Latvia, and Estonia based on multiple CE dimensions (Grybaitė et al., 2022; Kaya et al., 2023).

Previous research has demonstrated the effectiveness of TOPSIS in ranking sustainability performance. Nafei et al. (2024) successfully applied these methods to assess CE strategies in different regions, concluding that multi-criteria decision-making approaches offer robust and transparent evaluations. This study builds on these findings by applying MCDM techniques to CE assessment in the Baltic states (Nafei et al., 2024).

Cerchione et. al. (2024) studied on CE performance has often relied on single indicators or qualitative assessments, limiting the ability to capture the complexity of sustainability transitions. This study fills an important gap by adopting a multi-criteria approach to compare CE performance in Lithuania, Latvia, and Estonia, providing policymakers with actionable insights to enhance sustainability strategies in the region. The findings will contribute to the ongoing discourse on Circular Economy assessment and offer a replicable framework for evaluating CE performance in other regions (Cerchione et al., 2024).

Furthermore, while MCDM method such as TOPSIS have been successfully used in sustainability assessments, few studies have applied them comprehensively to rank CE performance across multiple countries using Eurostat data. The Baltic states Lithuania, Latvia, and Estonia present an interesting case for analysis due to their shared EU regulatory framework yet differing levels of CE implementation.

This study aims to fill this research gap by systematically evaluating and ranking the CE performance of these three countries using a multi-method MCDM approach. By integrating multiple CE indicators into a structured decision-making framework, this research will provide a comprehensive, objective, and data-driven ranking of CE progress in the Baltic region. The findings will help policymakers identify strengths and weaknesses in national CE strategies, ultimately guiding more effective sustainability policies to align with EU and global CE objectives. Table 1 shows the indicators with the categories and positive or negative impact on the economy.

Table 1. Circular Economy (CE) indicators from Eurostat (Coelho, 2022)

Notation	Category	Indicator	Most recent period	Type
C1	Production and consumption	Material footprint	2023	C
C2	Production and consumption	Resource productivity	2023	B
C3	Production and consumption	Waste generation per capita	2020	C
C4	Production and consumption	Generation of waste excluding major mineral wastes per GDP Unit	2022	C
C5	Production and consumption	Generation of municipal waste per capita	2022	C
C6	Production and consumption	Food waste	2022	C
C7	Production and consumption	Generation of packaging waste per capita	2022	C
C8	Production and consumption	Generation of plastic packaging waste per capita	2022	C
C9	Waste management	Recycling rate of municipal waste	2022	B
C10	Waste management	Recycling rate of all waste excluding major mineral waste	2022	B
C11	Waste management	Recycling rate of packaging waste by type of packaging	2022	B
C12	Waste management	Recycling rate of waste of electrical and electronic equipment (WEEE)	2022	B
C13	Secondary raw materials	Circular material use rate	2023	B
C14	Secondary raw materials	Contribution of recycled materials to raw materials demand – end-of-life recycling input rates (EOL-RIR)	2022	B
C15	Secondary raw materials	Trade in recyclable raw materials	2023	B
C16	Competitiveness and innovation	Private investment and gross added value related to CE sectors	2021	B
C17	Competitiveness and innovation	Persons employed in Circular Economy sectors	2021	B

End of Table 1

Nota-tion	Category	Indicator	Most recent period	Type
C18	Competitiveness and innovation	Patents related to recycling and secondary raw materials	2021	B
C19	Global sustainability and resilience	Consumption footprint	2022	C
C20	Global sustainability and resilience	Greenhouse gas emissions from production activities	2023	C
C21	Global sustainability and resilience	Material import dependency	2023	C
C22	Global sustainability and resilience	EU self-sufficiency for raw materials	2023	B

This study contributes to the literature by developing a robust multi-method MCDM framework (TOPSIS, MABAC, and COPRAS) to evaluate CE performance across the Baltic States using 22 Eurostat-based indicators. The methodology is replicable and objective benchmarking tool for regional and EU-level policy design.

3. Methodology

This study aims to assess and rank the Circular Economy (CE) performance of Estonia (A1), Latvia (A2), and Lithuania (A3) by analyzing 22 key indicators obtained from the Eurostat database. These indicators encompass various dimensions of sustainability, including resource consumption, waste management efficiency, recycling rates, secondary raw material use, investment in Circular Economy sectors, and environmental impact.

The first step involves selecting the 22 CE indicators, ensuring they comprehensively reflect the economic, environmental, and resource efficiency aspects of circularity. Since these indicators have different measurement units and scales, a data normalization process is applied to facilitate comparability and eliminate bias.

Following data preprocessing, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is employed to rank the three Baltic states. TOPSIS, a widely used Multi-Criteria Decision-Making (MCDM) method, is chosen for its ability to evaluate multiple criteria simultaneously and provide an objective ranking based on proximity to an ideal solution.

The ranking process involves calculating the relative performance scores for each country (A1, A2, A3) by comparing their distances from the positive ideal solution (PIS) and negative ideal solution (NIS). A country closer to the ideal solution exhibits a higher Circular Economy performance. Indicator Weighting Scheme. In this study, equal weights were assigned to all 22 Circular Economy indicators. This decision was made to maintain objectivity and neutrality in the absence of expert-derived or stakeholder-assigned weights. Equal weighting is a common approach in MCDM applications when no prior preference or reliable judgment exists to differentiate between indicators (Gyani et al., 2022). While this method simplifies analysis and avoids potential biases, it also assumes that all indicators contribute equally to Circular Economy performance. This may not reflect the true importance of each dimension, and thus, future studies are encouraged to apply weighting schemes derived from methods such as AHP or Delphi to enhance contextual relevance.

Finally, the study interprets the results to identify strengths, weaknesses, and policy gaps in CE implementation across Estonia, Latvia, and Lithuania. The findings provide valuable insights for policymakers, industry stakeholders, and sustainability researchers, offering a data-driven approach to improving Circular Economy strategies in the Baltic region. Figure 1 shows the research framework of this study.

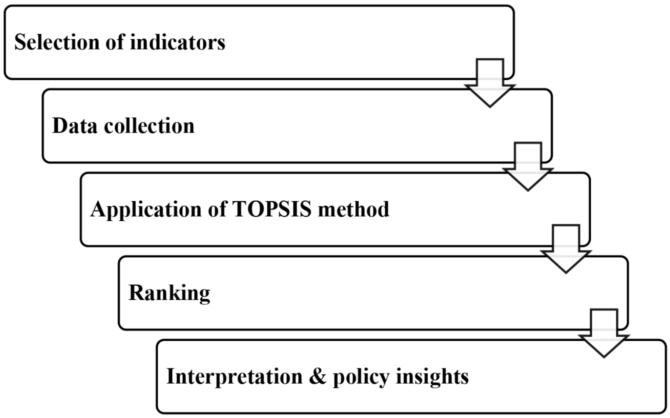

Figure 1. Research framework

TOPSIS is based on the assumption that the best solution has the shortest distance from the positive-ideal solution, and the longest distance from the negative-ideal one. Alternatives are ranked with the use of an overall index calculated based on the distances from the ideal solutions (Štreimikienė et al., 2024; Zhao et al., 2022).

The TOPSIS method proceeds as per following procedure:

Step 1. In the first step, criteria and alternatives of the decision problem are determined.

Step 2. Then, decision matrix X is constructed as:

$$\mathbf{X} = \left[\mathbf{x_{ij}}\right]_{\mathbf{I*J}} = \begin{bmatrix} \mathbf{x}_{11} & \mathbf{x}_{12} & \cdots & \mathbf{x}_{1\mathbf{J}} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{x}_{\mathbf{I}1} & \mathbf{x}_{\mathbf{I}2} & \cdots & \mathbf{x}_{\mathbf{IJ}} \end{bmatrix}. \quad (1)$$

Step 3. Calculate the normalised performance ratings. Vector normalisation is applied to obtain normalised performance ratings. In this procedure, each performance rating x_{ij} in X is divided by its norm. The normalised ratings y_{ij} $\left(i = 1, 2, \ldots, I;\ j = 1, 2, \ldots, J\right)$ can be calculated by:

$$y_{ij} = x_{ij} \,/\left(\sum_{i=1}^{I} x_{ij}^2\right)^{1/2}. \quad (2)$$

The normalised performance ratings y_{ij} can be given as a matrix Y as shown in Eq. (3).

$$\mathbf{Y} = \begin{bmatrix} \mathbf{y}_{11} & \mathbf{y}_{12} & \cdots & \mathbf{y}_{1\mathbf{J}} \\ \mathbf{y}_{21} & \mathbf{y}_{22} & & \mathbf{y}_{2\mathbf{J}} \\ \vdots & & \ddots & \vdots \\ \mathbf{y}_{\mathbf{I}1} & \mathbf{y}_{\mathbf{I}2} & \cdots & \mathbf{y}_{\mathbf{IJ}} \end{bmatrix}. \quad (3)$$

Step 4. Integrate weight and rating information. The weighted and normalised performance rating $v_{ij}\ (i = 1,2,\ldots,I;\ j = 1,2,\ldots,J)$ is calculated as:

$$v_{ij} = W_j y_{ij};\ \ i = 1,2,\ldots,I;\ \ j = 1,2,\ldots,J. \tag{4}$$

The weighted normalised rating matrix is then defined as:

$$\boldsymbol{V} = \begin{bmatrix} \boldsymbol{v}_{11} & \boldsymbol{v}_{12} & \cdots & \boldsymbol{v}_{1J} \\ \boldsymbol{v}_{21} & \boldsymbol{v}_{22} & & \boldsymbol{v}_{2J} \\ \vdots & & \ddots & \vdots \\ \boldsymbol{v}_{I1} & \boldsymbol{v}_{I2} & \cdots & \boldsymbol{v}_{IJ} \end{bmatrix}. \tag{5}$$

Step 5. Find positive and negative ideal solutions. A^* and A^- are denoted as the positive and negative ideal solution sets respectively which can be denoted as:

$$A^* = \left[v_1^*, v_2^*, \ldots, v_J^*\right] \tag{6}$$

and

$$A^- = \left[v_1^-, v_2^-, \ldots, v_J^-\right], \tag{7}$$

where, $v_j^* = \left\{\max_i v_{ij}, j \in B;\ \min_i v_{ij}, j \in C\right\}$ and $v_j^- = \left\{\min_i v_{ij}, j \in B;\ \max_i v_{ij}, j \in C\right\}$ where B and C are the subsets of benefit and cost criteria respectively.

Step 6. Obtain the separation values. The separation measure is the distance of each alternative rating from both the positive and negative ideal solutions which is obtained by applying the Euclidean distance. The Euclidean distances to the ideal alternatives are obtained as:

$$S_i^* = \left(\sum_{j=1}^{J}\left(v_{ij} - v_j^*\right)^2\right)^{1/2}; \tag{8}$$

$$S_i^- = \left(\sum_{j=1}^{J}\left(v_{ij} - v_j^-\right)^2\right)^{1/2}. \tag{9}$$

Step 7. Calculate the overall preference score. The overall preference score V_i for each alternative A_i is obtained as:

$$V_i = \frac{S_i^-}{S_i^- + S_i^*}. \tag{10}$$

Alternatives are ranked based on higher V_i values.

4. Results

The first step involved collecting data for 22 Circular Economy indicators (Table 1) from the Eurostat database for Estonia (A1), Latvia (A2), and Lithuania (A3). This matrix represents the raw data before any transformation or standardization. Table 2 shows the initial matrix for analysis of the CE development.

Table 2. Initial decision matrix for Estonia (A1), Latvia (A2), and Lithuania (A3)

Criterion	A1	A2	A3	Weight
C1	29.635	19.828	22.719	0.045455
C2	0.6372	0.8965	0.7949	0.045455
C3	12163	1501	2396	0.045455
C4	470	85	96	0.045455
C5	373	464	465	0.045455
C6	134	124	140	0.045455
C7	143.21	153.44	151.12	0.045455
C8	33.83	26	37.81	0.045455
C9	33.2	50.8	48.4	0.045455
C10	50	45	55	0.045455
C11	73	60.8	58.3	0.045455
C12	80.8	82.7	81.8	0.045455
C13	18.1	5	3.9	0.045455
C14	15	13	14	0.045455
C15	23658	679333	495055	0.045455
C16	200	233	447	0.045455
C17	14152	24105	39115	0.045455
C18	150	130	140	0.045455
C19	107	105	108	0.045455
C20	7669.508	5236.378	7131.532	0.045455
C21	19.2	28.6	34.2	0.045455
C22	40	38	42	0.045455

Since the indicators have different measurement units, *vector normalization* is applied to standardize the values. Each value is divided by the square root of the sum of squares of the column. Table 3 shows the normalized matrix.

Table 3. Normalized matrix

Criterion	A1	A2	A3
C1	0.700935	0.468977	0.537356
C2	0.469546	0.660621	0.585753
C3	0.97403	0.120202	0.191875
C4	0.964743	0.174475	0.197054
C5	0.493769	0.614233	0.615557
C6	0.582433	0.538967	0.608512
C7	0.553722	0.593277	0.584307
C8	0.593412	0.456066	0.663225

End of Table 3

Criterion	A1	A2	A3
C9	0.427704	0.654439	0.623521
C10	0.575435	0.517892	0.632979
C11	0.654912	0.545461	0.523032
C12	0.570499	0.583914	0.57756
C13	0.943759	0.260707	0.203351
C14	0.61754	0.535202	0.576371
C15	0.028134	0.807853	0.588712
C16	0.368794	0.429645	0.824255
C17	0.294367	0.501392	0.813606
C18	0.61754	0.535202	0.576371
C19	0.579115	0.56829	0.584527
C20	0.655012	0.447211	0.609066
C21	0.395541	0.589191	0.704557
C22	0.57687	0.548026	0.605713

The positive ideal solution (PIS) is the highest value for beneficial indicators, and the negative ideal solution (NIS) is the lowest value for non-beneficial indicators. Table 4 shows the ideal solution based on calculation.

Table 4. Ideal solutions

Criterion	A*	A-
C1	0.021317	0.031861
C2	0.030028	0.021343
C3	0.005464	0.044274
C4	0.007931	0.043852
C5	0.022444	0.02798
C6	0.024499	0.02766
C7	0.025169	0.026967
C8	0.02073	0.030147
C9	0.029747	0.019441
C10	0.028772	0.023541
C11	0.029769	0.023774
C12	0.026542	0.025932
C13	0.042898	0.009243
C14	0.02807	0.024327
C15	0.036721	0.001279
C16	0.037466	0.016763

End of Table 4

Criterion	A*	A-
C17	0.036982	0.01338
C18	0.02807	0.024327
C19	0.025831	0.026569
C20	0.020328	0.029773
C21	0.017979	0.032025
C22	0.027532	0.02491

Using Euclidean distance, the separation measures (Si+ and Si-) from the ideal solutions are calculated. Table 5 shows the final ranking.

Table 5. Final ranking using TOPSIS

Alternatives	S_i^+	S_i^-	C_i	Ranking
A1	0.0740	0.0381	0.340	3
A2	0.0410	0.0683	0.625	1
A3	0.0411	0.0658	0.615	2

Latvia (A2) achieved the highest ranking (Ci = 0.625), suggesting a better Circular Economy performance than Estonia and Lithuania. Lithuania (A3) ranked second (Ci = 0.615), showing moderate performance. Estonia (A1) ranked last (Ci = 0.340), indicating lower efficiency in CE implementation along with a substantial gap compared to the preceding countries.

Latvia emerged as the best-performing country in terms of Circular Economy practices, driven by strong waste management policies, higher recycling rates, and efficient resource use. The country performed exceptionally well in indicators related to waste management efficiency, including the Recycling Rate of Municipal Waste (C9), Recycling Rate of All Waste (C10), and Circular Material Use Rate (C13). These results suggest that Latvia has developed a well-structured waste management system that effectively promotes recycling and minimizes landfill waste.

Furthermore, Latvia demonstrated relatively high private investment in CE sectors (C16), which indicates that the government and private sector are actively supporting sustainability initiatives. This investment may have contributed to Latvia's progress in improving material efficiency and secondary raw material use.

Additionally, Latvia's Material Footprint (C1) was lower than that of Estonia and Lithuania, meaning that the country consumes fewer raw materials per capita. This is a positive indicator of resource efficiency and sustainable consumption practices. Similarly, Latvia's Resource Productivity (C2) was higher than Estonia's, reflecting the country's ability to generate more economic value per unit of material used.

Despite these achievements, Latvia still faces challenges in reducing material import dependency (C21). High reliance on imported raw materials can make the economy vulnerable to global supply chain disruptions. Addressing this issue through policies that encourage domestic material sourcing and increased use of secondary raw materials could further strengthen Latvia's CE performance.

Lithuania ranked second in CE performance, demonstrating notable strengths in investment, recycling efficiency, and secondary raw material use. The country showed strong performance in Trade in Recyclable Raw Materials (C15), suggesting that it plays a key role in the regional Circular Economy by exporting and utilizing secondary materials.

Moreover, Lithuania performed well in Private Investment in CE Sectors (C16) and Persons Employed in Circular Economy Sectors (C17), indicating that the country has made progress in promoting employment and economic activity within sustainability-focused industries. These factors contribute to Lithuania's efforts to transition toward a greener economy by increasing financial and human capital in circular activities.

However, Lithuania showed moderate performance in waste generation indicators. The Generation of Municipal Waste Per Capita (C5) and Food Waste (C6) were relatively high compared to Latvia, suggesting that there is room for improvement in waste reduction efforts. Additionally, Lithuania's Material Import Dependency (C21) was the highest among the three Baltic states, highlighting a reliance on imported materials. This dependency may pose challenges in the long run, particularly in times of supply chain disruptions or price fluctuations.

Estonia ranked last in the TOPSIS evaluation, indicating that it faces the most challenges in achieving Circular Economy goals. The country performed poorly in material efficiency indicators, particularly in Material Footprint (C1) and Resource Productivity (C2). A high material footprint suggests that Estonia consumes more raw materials per capita, which could be linked to industrial activities and inefficient resource utilization.

Additionally, Estonia exhibited the highest Waste Generation Per Capita (C3) among the three countries, suggesting that consumption and disposal practices need to be improved. The Generation of Waste Excluding Major Mineral Wastes Per GDP Unit (C4) was also significantly higher than in Latvia and Lithuania, highlighting inefficiencies in industrial and municipal waste management.

While Estonia has made some progress in Recycling Rates (C9–C12), its performance in these indicators was not sufficient to compensate for its weaknesses in resource efficiency and waste generation. The country also had lower investments in Circular Economy sectors (C16) compared to Lithuania and Latvia, which may indicate a lack of strong financial incentives or policy support for CE development.

One area where Estonia performed slightly better was in Greenhouse Gas Emissions from Production Activities (C20). Despite its lower ranking overall, Estonia had slightly lower emissions per capita than Lithuania, which suggests that the country has implemented some level of emission reduction policies in industrial sectors.

The results of this study provide important insights for policymakers and sustainability experts in the Baltic states. The findings suggest that Latvia leads in Circular Economy performance, particularly in waste management and recycling. To maintain and further improve its performance, Latvia should focus on reducing import dependency and increasing domestic material self-sufficiency.

Lithuania, although ranking second, shows strong investment and employment trends in CE sectors, indicating a positive trajectory toward sustainability. However, the country needs to improve waste reduction efforts and reduce its reliance on imported raw materials.

Estonia, which ranked the lowest, faces significant challenges in waste generation and material efficiency. The country should prioritize policies that promote resource optimization, circular production models, and financial incentives for sustainability investments.

Future research should incorporate a formal sensitivity test for TOPSIS, such as bootstrapping or weight variation analysis, to enhance methodological rigor. Additionally, extending the analysis to other regions or applying stakeholder-driven weighting methods (e.g., AHP or Delphi) would increase the applicability and relevance of the framework in diverse policy contexts.

5. Discussion

This study set out to assess and rank the Circular Economy performance of Estonia, Latvia, and Lithuania using a data-driven approach based on 22 key indicators. By utilizing the TOPSIS method, a widely recognized Multi-Criteria Decision-Making (MCDM) approach, the research provided an objective ranking of these three Baltic countries, highlighting their strengths, weaknesses, and areas requiring further policy attention. The findings contribute to a better understanding of how effectively each country has implemented Circular Economy principles and provide insights into their progress toward sustainability goals.

The methodology followed a structured approach, beginning with the selection of relevant Circular Economy indicators that represent various dimensions of sustainability, including resource consumption, waste management efficiency, recycling performance, secondary raw material use, economic investment, and environmental impact. Given that these indicators are measured in different units and scales, a normalization process was applied to ensure comparability before ranking the countries using the TOPSIS method. This allowed for a systematic evaluation of their relative performance based on their proximity to an ideal Circular Economy scenario.

The results revealed notable differences in Circular Economy implementation across the three countries. Latvia emerged as the leader in Circular Economy performance, with the highest TOPSIS score, indicating strong waste management practices, higher recycling rates, and greater efficiency in resource utilization. The country has demonstrated a commitment to sustainability through significant investments in Circular Economy sectors and high employment in related industries. However, Latvia still faces challenges, particularly in reducing its dependency on imported materials, which could make its Circular Economy model vulnerable to external supply chain disruptions.

Lithuania ranked second, closely following Latvia. The country performed well in terms of private investment in Circular Economy sectors and trade in recyclable materials, indicating its role as a key player in the regional Circular Economy network. Additionally, Lithuania showed promising employment trends in sustainability-focused industries, suggesting that the Circular Economy transition is creating economic opportunities. However, despite these strengths, Lithuania exhibited moderate performance in waste generation indicators, particularly in food waste and municipal waste per capita. Addressing these challenges could further strengthen Lithuania's position as a Circular Economy leader in the Baltic region (Lankauskienė et al., 2022).

Estonia ranked last in the evaluation, indicating significant challenges in implementing Circular Economy principles. The country had the highest material footprint and waste generation per capita among the three, suggesting inefficiencies in resource use and waste management (Zappala, 2023). Lower investment in Circular Economy sectors and limited improvements in recycling rates further contributed to Estonia's lower ranking. One area where Estonia performed slightly better was in greenhouse gas emissions from production activities, which were lower than in Lithuania (Ūsas et al., 2025). However, this was not sufficient to offset the country's weaknesses in other key Circular Economy indicators. To improve its performance, Estonia needs to focus on resource optimization, reducing waste generation, and increasing investment in Circular Economy initiatives.

While this study provides valuable insights into Circular Economy performance in the Baltic states, it also has some limitations. One of the key challenges was data availability and completeness. Although Eurostat provides extensive data on Circular Economy indicators, some values were missing or outdated, which may have affected the accuracy of the rankings. Future research could address this limitation by incorporating additional data sources or expert assessments to fill these gaps.

Another limitation was the assumption of equal weighting for all indicators in the TOPSIS evaluation. In reality, some indicators may have a greater impact on Circular Economy performance than others. For example, waste generation and recycling efficiency are likely to be more critical factors than other indicators, such as trade in recyclable raw materials. Future studies could refine the weighting system by incorporating expert opinions using methods like the Analytic Hierarchy Process (AHP) or Delphi technique to assign more realistic weightings to each indicator.

Furthermore, this study primarily focused on quantitative data analysis and did not include an in-depth examination of Circular Economy policies and regulatory frameworks in each country. While the numerical rankings provide an objective comparison, they do not fully capture the effectiveness of national policies, government initiatives, or industry-led sustainability efforts. A qualitative analysis of policy measures and stakeholder perspectives could complement these findings and provide a more comprehensive understanding of Circular Economy implementation.

Despite these limitations, the findings of this study have important implications for policymakers, industry leaders, and sustainability researchers. The results highlight the need for targeted policy interventions to strengthen Circular Economy practices in the Baltic region. Latvia's strong performance suggests that waste management and recycling policies are yielding positive results, but further efforts are needed to reduce material dependency (Anselmi et al., 2024). Lithuania's progress in investment and employment indicates that economic opportunities exist within the Circular Economy transition, but waste reduction strategies should be prioritized (Mazur-Wierzbicka, 2021). Estonia, on the other hand, requires significant improvements in resource efficiency and financial incentives to support Circular Economy initiative (Ahmadov et al., 2022).

By addressing these challenges and leveraging their strengths, Estonia, Latvia, and Lithuania can enhance their Circular Economy strategies and align with the European Union's long-term sustainability objectives. Future research should build on this study by incorporating additional methodologies, expanding the scope of analysis, and exploring policy interventions that can accelerate the transition to a more resource efficient economy.

6. Conclusions

This study aimed to assess and rank the Circular Economy performance of Estonia, Latvia, and Lithuania using a structured, data-driven approach. By analyzing 22 key indicators from the Eurostat database and applying the TOPSIS method, the research provided an objective comparison of how effectively each country has implemented Circular Economy principles. The findings revealed that Latvia leads in Circular Economy performance, followed closely by Lithuania, while Estonia lags behind due to inefficiencies in resource use, waste management, and investment in sustainability. These results offer valuable insights into the progress and challenges faced by each country in their transition toward a more circular and resource-efficient economy.

Despite the contributions of this study, there are certain limitations that should be acknowledged. One key challenge was the availability and completeness of data. While Eurostat provides extensive information on Circular Economy indicators, some datasets had missing values or inconsistencies, which may have influenced the accuracy of the rankings. Additionally, the study applied equal weighting to all indicators, assuming that each factor contributes equally to Circular Economy performance. However, in reality, some indicators may have a greater impact than others, requiring a more nuanced weighting approach based on expert opinions or alternative MCDM techniques.

Another limitation of this research is its focus on quantitative data without an in-depth examination of Circular Economy policies and regulatory frameworks in each country. While numerical rankings offer an objective comparison, they do not fully capture the effectiveness of government initiatives, industry participation, or stakeholder engagement in Circular Economy implementation. A more comprehensive assessment would integrate both quantitative and qualitative approaches to better understand the policy landscape and the drivers behind successful Circular Economy transitions.

Future research should address these limitations by incorporating additional methodologies, such as expert-based weighting techniques or hybrid MCDM models, to refine the ranking process. Expanding the scope of the study to include other European countries with advanced Circular Economy models could also provide valuable benchmarking insights. Furthermore, integrating a policy analysis framework would help evaluate the effectiveness of different regulatory approaches and identify best practices for enhancing Circular Economy performance. By building on these findings, future studies can offer more targeted recommendations to support the transition toward a sustainable and Circular Economy in the Baltic region and beyond.

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The authors contributed equally to the elaboration of this research.

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