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ECONOMIC COMPETITIVENESS AND SUSTAINABILITY 2026

PROCEEDINGS

March 26th–27th, 2026, Brno

Editors:
Petr David
Hana Vránová

MENDELU
Faculty
of Business
and Economics

Mendel University in Brno
Faculty of Business and Economics

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Czech Republic

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Faculty
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and Economics

2026

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ABSTRACT

On March 26th and 27th, 2026, the Faculty of Business and Economics of Mendel University in Brno organized already the 28th international conference "Economic Competitiveness and Sustainability" with over 100 onsite participants from around the world. In the presented Proceedings you find 44 papers which were recommended by conference discussants and selected on the basis of a peer-review process. The presented research outputs contribute to and extend the current state of the art and will stimulate further debate not only in academia but also in other institutions of public and private sector. The published papers address current interdisciplinary challenges arising at the intersection of digital transformation, artificial intelligence, sustainability, enterprise information systems, finance, public policy, marketing, and management. Together, they demonstrate the growing importance of data-driven approaches, intelligent technologies, and sustainable solutions in addressing contemporary economic and societal challenges.

Keywords: artificial intelligence, digital transformation, information systems, economics and finance, marketing and consumer behaviour, sustainability

ABSTRAKT

Ve dnech 26. a 27. března 2026 uspořádala Provozně ekonomická fakulta Mendelovy univerzity v Brně již 28. ročník mezinárodní konference „Economic Competitiveness and Sustainability", kterého se zúčastnilo přes 100 účastníků z celého světa. V předloženém sborníku najdete 44 příspěvků, které byly doporučeny diskutanty konference a vybrány na základě recenzního řízení. Prezentované výstupy výzkumu přispívají a rozšiřují současný stav poznání a podněcují další diskusi nejen na akademické půdě, ale i v rámci veřejného a soukromého sektoru. Publikované příspěvky reflektují současné interdisciplinární výzvy vznikající na průsečíku digitální transformace, umělé inteligence, udržitelnosti, podnikových informačních systémů, financí, veřejné správy a hospodářské politiky, marketingu a managementu. Současně poukazují na rostoucí význam datově podloženého rozhodování, inteligentních technologií a udržitelných řešení pro zvládání aktuálních ekonomických a společenských výzev.

Klíčová slova: umělá inteligence, digitální transformace, informační systémy, ekonomie a finance, marketing a spotřebitelské chování, udržitelnost

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FOREWORD

Dear readers,

We are honoured to present you with the Conference Proceedings we are publishing as the one of the outputs of the 28th year of the International Conference Economic Competitiveness and Sustainability (ECOS 2026) that we organised in March 26–27, 2026. The conference traditionally takes place in the campus of the Mendel University in Brno, Czech Republic and provides a productive background for the development of new ideas not only for senior but also for young researchers.

We hosted two distinguished well-known speakers who contributed to the conference programme with their keynote speeches. Prof. Gonul Colak (Head of Department of Accounting and Finance, University of Sussex Business School, UK) gave a speech "Government Debt, Corporate Debt, and Financial Crowding-In: A Cross-Country Analysis". Prof. Tomas Jandik (Finance and Dillard's Chair in Corporate Finance, Sam M. Walton College of Business, University of Arkansas, USA) contributed to the discussion on the topic of "Networks Everywhere: How Connectedness Shapes Risk, Information, and Value".

We welcomed more than 100 researchers representing universities and research institutes from countries including Czech Republic, Albania, France, Germany, Hungary, Lithuania, Malaysia, Poland, Serbia, Slovakia, Ukraine and USA, who also served as the discussants of the papers and helped to improve the quality of the research results presented during both conference days.

Another useful opportunity to discuss the conference themes was a moderated Panel Discussion entitled "Ethics, Excellence, and Algorithms: AI's Future in Academia", with five invited experts: Gonul Colak, Tomas Jandik, Adéla Lekešová (AI consultant, BDO Czech Republic), Kamil Malinka (Department of Intelligent Systems, Brno University of Technology) and Tomáš Pitner (Professor at Mendel University in Brno).

The purpose of the conference is to enhance academic debate on current problems in the global socio-economic environment and dynamic technological development. Last but not least it is a chance to meet our research counterparts in person and critically review our perspectives on contemporary research problems.

In the presented Proceedings you can find 44 papers that were recommended by conference discussants and selected on the basis of a careful peer-review process. The papers cover a broad spectrum of topics including artificial intelligence, cybersecurity, information systems, finance, sustainability, public policy, consumer behaviour, and digital innovation. The published papers also underwent a thorough plagiarism detection process.

We would like to thank all the participants in the conference for their inspiring contributions. Furthermore, we are grateful to all the discutants, reviewers and the members of the scientific committee for their contribution to the scientific level of presented papers and organisation of this international scientific conference.

ECONOMIC COMPETITIVENESS AND SUSTAINABILITY 2026

CONTRIBUTIONS

CIRCULAR ECONOMY INDICATORS AND DIGITAL TRANSFORMATION: ASSESSING THE RELATIONSHIP BETWEEN ERP ADOPTION AND CIRCULAR ECONOMY PERFORMANCE ACROSS EU COUNTRIES

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ABSTRACT

The shift towards a circular economy requires the systematic integration of sustainability principles into economic and business processes, with digital technologies playing an increasingly important role. Among these, enterprise resource planning (ERP) systems represent an important tool, as they enable the collection, integration, and analysis of data crucial for enhancing resource efficiency and implementing circular economy principles. This study aims to examine the relationship between enterprise-level digitalization, ERP system adoption, and circular economy performance at the country level by using circular economy (CE) indicators across European Union member states. The research adopts a two-phase methodological approach. In the first phase, the TOPSIS multi-criteria decision-making method was applied to rank EU member states based on a set of relevant CE indicators. In the second phase, the resulting TOPSIS scores were used to examine the relationships among circular economy performance, digitalisation, and ERP system adoption using regression analysis and a group-based comparative technique. The results confirm pronounced differences in the performance of the circular economy across the member states of the European Union, with innovative and industrially advanced countries occupying leading positions in the TOPSIS ranking. At the same time, the findings indicate that digitisation at the enterprise level, including the adoption of ERP systems and ICT technologies, is positively associated with circular economy outcomes at the macro-country level, but by itself is not sufficient to achieve high performance without adequate structural and innovation capacities. The findings should be interpreted as macro-level associations rather than direct causal effects, as the study relies on aggregated country-level indicators and proxy measures of enterprise digitalisation.

Keywords: circular economy, ERP systems, digital transformation, sustainability indicators
JEL: Q56, O33, M15, C44

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1 INTRODUCTION

The transition to a circular economy is one of the European Union's key strategic priorities in pursuing sustainable development, climate neutrality, and long-term economic resilience (European Commission, 2020; Kirchherr *et al.*, 2017). For a long time, the economy has followed a simple, linear path: extracting resources from the earth, manufacturing products, and discarding them after use. This linear model, often summarised as "take-make-dispose", assumes resources are infinite and waste is an inevitable byproduct. Unlike the traditional linear model, the circular economy focuses on efficient resource use, extending product life cycles, and recycling and reusing materials, thereby reducing the negative environmental impacts of economic activities (Geissdoerfer *et al.*, 2017; Ghisellini *et al.*, 2016). The shift from a linear to a circular economy is a fundamental change, requiring a rethinking not only of waste management but also of how we design, produce, and use products. A circular economy is designed to eliminate waste and keep resources in use for as long as possible. Instead of a straight line ending in landfill, it forms a closed loop. This transition is progressing well across Europe, with clear objectives and increasing momentum for change. To support this shift, the European Union has established a comprehensive monitoring framework to assess circular economy performance, covering a wide range of environmental, economic, and innovation-related indicators (European Commission, 2023).

Concurrently, digital transformation has increasingly been recognized as a key enabler of the shift towards more sustainable economic models. Digital technologies facilitate the collection, processing and analysis of large volumes of data, enhance the transparency of business processes, and support data-driven decision-making (Brynjolfsson & McAfee, 2014). In this context, integrated information systems, particularly enterprise resource planning (ERP) systems, play a pivotal role by linking diverse business functions and enabling the systematic monitoring of resource flows, waste generation and emissions (Seidel *et al.*, 2017).

Despite increasing scholarly interest in the relationship between digitalization and sustainability, much existing research remains focused on the micro level or treats digitalization and sustainability as broad, abstract concepts. Consequently, limited attention has been paid to examining the specific mechanisms through which digital transformation affects circular economy performance at the macro level (de Sousa Jabbour *et al.*, 2020; Rosa *et al.*, 2020). In particular, there is a notable lack of comparative empirical studies that simultaneously analyses circular economy performance, the level of digitalization, and the adoption of ERP systems across European Union member states. To address this research gap, the present study aims to rank European Union member states according to their level of circular economy development and to examine the role of digital transformation and ERP systems in explaining observed cross-country differences in performance. The indicators employed in this study primarily operate at the macro-country level and are intended for comparative assessment and benchmarking of circular economy performance across European Union member states. Accordingly, the analysis does not interpret circular economy indicators as direct measures of firm-level ERP performance, but rather examines whether higher levels of enterprise digitalization and ERP adoption at the national level are associated with stronger circular economy outcomes. Furthermore, the selected indicators predominantly reflect resource efficiency, recycling performance, and material flow dimensions of the circular economy monitoring framework, while acknowledging that certain broader circular economy dimensions, such as regenerative and product life-extension aspects, remain more difficult to capture through currently available harmonized cross-country data. In line with recent circular economy indicator taxonomies, the indicators used in this study primarily belong to the macro-level monitoring domain and are intended to

support benchmarking and comparative policy assessment across countries rather than firm-level operational monitoring. Consequently, the study does not claim that circular economy indicators are directly embedded into ERP architectures or enterprise data infrastructures. Instead, ERP adoption and enterprise digitalisation are treated as macro-level proxy variables reflecting the broader digital readiness of national economies and their potential alignment with circular economy outcomes. To achieve this objective, the study adopts a two-phase methodological approach. In the first phase, the multi-criteria decision-making method TOPSIS is used to rank EU countries based on their circular economy performance (Mardani *et al.*, 2018). In the second phase, the resulting TOPSIS scores are used to analyses the relationship between circular economy performance, digitalization, and ERP system adoption using regression analysis and a group-based comparative technique (Afolabi, 2025; Karnaushenko, 2025; Gil-Lamata, 2024).

The findings contribute to a deeper understanding of the complex relationship between digital transformation and sustainability at the macro level. Specifically, the results indicate that digitalization and ERP systems are important enabling factors for the development of a circular economy, while their overall impact depends on broader institutional, economic, and regulatory conditions (Karnaushenko, 2025; Parida *et al.*, 2019). In addition to its theoretical contribution, the study provides practical insights for policymakers shaping digital transformation strategies and circular economy policies within the European Union.

2 LITERATURE REVIEW

Recent circular economy literature increasingly distinguishes between different levels and purposes of circular economy indicators, including micro-, meso-, and macro-level indicators designed for monitoring, benchmarking, communication, and policy evaluation purposes. Existing taxonomies also differentiate indicators according to the dimensions of circularity they capture, such as slowing resource loops, closing material loops through recycling, extending product lifecycles, and regenerative resource use. Due to limitations in harmonised EU-wide data availability, the present study primarily focuses on macro-level indicators associated with resource efficiency, recycling performance, secondary raw material use, and sustainability pressures, while acknowledging that regenerative and product life-extension dimensions remain less represented. Recent research increasingly regards the circular economy (CE) as a multi-dimensional policy and performance domain, typically assessed by indicators measuring resource efficiency, waste management, secondary materials, and innovation outcomes. Given the inherently multidimensional nature of CE progress, a growing body of studies uses composite indicators and cross-country rankings to improve comparability and inform policy interpretation across EU member states (Grybaitė & Burinskienė, 2024).

In recent years, the use of multi-criteria decision-making (MCDM) methods has increased significantly in EU-focused circular economy (CE) assessments, as MCDM provides a transparent means of combining diverse indicators into a single performance score. For example, Stanković *et al.* (2021) propose an integrated PCA-PROMETHEE approach to develop a composite index of CE development for EU countries, showing how rankings and clusters can be generated from a structured set of indicators. Similarly, Grybaitė and Burinskienė (2024) use the SAW method to assess CE development across EU countries, offering an indicator-based ranking system that is easy to interpret and communicate in policy contexts. Robustness-oriented studies increasingly combine several MCDM techniques (PROMETHEE, SAW, TOPSIS) to evaluate the stability of rankings and identify which

criteria drive cross-country differences (Grybaitė & Burinskienė, 2024). Furthermore, the MCDM literature has broadened the evaluation scope by incorporating social dimensions of circularity. Kaya *et al.* (2023) focus on social factors within the CE concept for European countries, reinforcing the argument that CE performance is shaped by a broader socioeconomic context beyond purely material and waste indicators.

At the same time, the relationship between digital transformation and circular economy outcomes has attracted increasing academic interest. Macro-level evidence shows that digitalisation can advance the circular economy by enhancing monitoring, coordination, and data-driven decision--making. For example, Afolabi (2025) identifies digitalisation as a key driver of circular economy development in Europe, alongside eco-innovation and economic complexity, while highlighting heterogeneity in effects across countries. Related EU-focused research investigates whether digitalisation promotes circular economy trajectories and emphasises digital capacities as important preconditions for implementing circular practices and policies (Gil-Lamata, 2024). Within the broader digitalisation agenda, ERP systems are increasingly regarded as key infrastructures for

Tab. 1 Selected studies on circular economy indicators, MCDM methods, and digitalisation

Study (Year)	Data source	Circular economy focus	Methodological approach	Digitalisation / ERP dimension
Abobakr *et al*. (2025)	Literature review	Sustainability monitoring and reporting	Conceptual analysis	ERP systems
Anjaria, (2025)	Literature-based	CE-enabling practices	Conceptual framework	ERP systems
Grybaitė & Burinskienė, (2024)	EU monitoring framework	CE performance and criteria importance	SAW	Not included
Afolabi (2025)	Macro-level panel data	Drivers of CE advancement	Econometric analysis	Digitalisation
Gil-Lamata (2024)	Digital performance indicators + CE context	Digitalisation - CE nexus	Macro-level empirical analysis	Digitalisation (DESI-type indicators)
Kaya, Ayçin & Pamucar (2023)	Multi-source indicators	Social dimension of CE	Hybrid MCDM	Not included
Tighnavard Balasbaneh *et al*. (2025)	International sustainability indicators	CE performance assessment	Hybrid MCDM (ANP, TOPSIS)	Not included
Stanković *et al*. (2021)	Eurostat CE indicators (multi-year)	Overall CE development	PCA, PROMETHEE	Not included
Mardani *et al*. (2018)	Secondary indicators (cross-country)	Sustainability & CE evaluation	MCDM	Not included
Zavadskas *et al*. (2016)	Literature review	Sustainability issues	MCDM	Not included

sustainability management because they integrate operational and reporting data across business functions. Recent studies on sustainable ERP systems argue that ERP-enabled monitoring can support resource optimisation, lifecycle tracking, reverse logistics, and ESG reporting. However, realised benefits depend on data quality, organisational adoption, and governance practices (Anjaria, 2025; Abobakr *et al.*, 2025). Table 1 presents an overview of selected recent studies that examine circular economy indicators, apply multi-criteria decision-making methods, and explore the role of digitalisation and ERP systems in the context of the European Union.

As shown in Table 1, the existing literature on circular economy assessment has primarily focused on developing indicators and ranking countries using multi-criteria decision-making methods, while largely neglecting digital transformation and ERP system adoption as explanatory factors. More recent studies have begun to recognise the importance of digitalisation for advancing the circular economy. However, these studies typically examine digital performance in isolation and do not incorporate it into frameworks for evaluating circular economy outcomes. Furthermore, research explicitly addressing the role of ERP systems remains largely conceptual and is rarely analysed alongside macro-level circular economy indicators. In this context, the present study contributes to the field by integrating MCDM-based ranking of circular economy performance with empirical analysis of digital transformation and ERP system adoption across EU countries. This approach addresses a notable research gap and provides a more comprehensive perspective on the digital drivers of circular economy development.

3 METHODOLOGY

3.1 Data sources and sample

This research used a quantitative approach based on secondary data analysis, focusing on the member states of the European Union (EU-27) as the unit of analysis. The analysis covers data from 2020 to 2024, the most recent and comparable years available, ensuring the timeliness of the results and minimising the influence of short-term fluctuations. The data were obtained from the official Eurostat database.

3.2 Selection of circular economy indicators

The selection of circular economy indicators in this study is based on the EU circular economy monitoring framework and supported by recent empirical literature, which highlights the need for a structured and multidimensional approach to assessing circular economy performance at the macro level. To ensure analytical clarity and conceptual consistency, the indicators are grouped into five thematic categories, each representing a distinct dimension of circular economy development. Table 2 presents the evaluated criteria organised into these thematic categories of circular economy indicators.

The **Production and consumption** category includes indicators that capture resource efficiency and waste generation intensity. Resource productivity reflects an economy's ability to generate value with lower material inputs, while municipal waste generation per capita indicates the pressure that consumption patterns place on resource and waste management systems (Ghisellini *et al.*, 2016; Geissdoerfer *et al.*, 2017). Together, these indicators assess how closely production and consumption models align with circular economy principles. The **Waste management** category focuses on the effectiveness of systems designed to close material loops through recycling. Recycling rates of municipal waste and recycling rates of packaging waste by packaging type are

Tab. 2 List of categories and criteria

Category	Code	Criteria	Direction
Production and consumption	PC_1 PC_2	Resource productivity Generation of municipal waste per capita	MAX MIN
Waste management	WM_1 WM_2	Recycling rate of municipal waste Recycling rate of packaging waste by type of packaging	MAX MAX
Secondary raw materials	RM_1	Circular material use rate	MAX MAX
Competitivenes and innovation	CI_1 CI_2	Private investment and gross added value related to circular economy sectors Patents related to recycling and secondary raw materials	MAX MAX
Global sustainability and resilience	GS_1 GS_2 GS_3	Consumption footprint Greenhouse gases emissions from production activities Material import dependency	MIN MIN MIN

key measures of waste management performance and the reintegration of waste materials into economic processes (Ūsas *et al.*, 2025; Tighnavard Balasbaneh *et al.*, 2025). The **Secondary raw materials** category is represented by the circular material use rate, which measures the share of secondary materials in total material consumption. This indicator plays a central role in evaluating the degree of material circularity and is widely regarded as a core measure of circular economy progress (Stanković *et al.*, 2021; Kirchherr *et al.*, 2017). The **Competitiveness and innovation** dimension captures the economic and technological foundations of circular economy development. Private investment and gross value added related to circular economy sectors reflect the capacity of economies to foster innovation, scale circular business models, and enhance competitiveness. In addition, patents concerning recycling and secondary raw materials serve as a direct indicator of innovation activity and technological progress in the circular economy. Patent filings reflect the creation of new processes, materials, and technologies that improve resource efficiency, enable waste valorisation, and facilitate the replacement of primary raw materials (European Commission, 2023; Grybaitė & Burinskienė, 2024). Finally, the **Global sustainability and resilience** category encompasses indicators addressing broader systemic impacts. Consumption footprint, greenhouse gas emissions from production activities, and material import dependency provide insight into environmental pressures and structural vulnerabilities, highlighting the role of circular economy practices in supporting long-term sustainability and economic resilience (Stanković *et al.*, 2021; Grybaitė & Burinskienė, 2024; Ūsas *et al.*, 2025).

The selected indicators are consistent with recent empirical studies that use multi-criteria decision-making approaches to evaluate and rank circular economy performance across EU countries, highlighting the importance of integrating indicators within a unified analytical framework (Ūsas *et al.*, 2025; Grybaitė & Burinskienė, 2024). Their use also aligns with the European Commission's recommendations for monitoring progress towards a circular economy (European Commission, 2023). The optimisation direction for each criterion is specified in Table 2. Criteria for which higher values indicate better circular economy performance are considered benefit (MAX) criteria, while those for which lower values indicate more advantageous environmental or structural outcomes are classified as cost (MIN) criteria. This predefined approach ensures consistent normalisation and supports the application of multi-criteria decision-making methods.

3.3 Entropy-based weighting method

To objectively determine the relative importance of criteria in the model, this study applies the entropy-based weighting method. Entropy-based weighting was applied to objectively determine criterion importance based on data variability, following the information entropy concept introduced by Shannon (1948) and its subsequent application in multi-criteria decision-making methods (Wang & Lee, 2007). The underlying assumption of this approach is that criteria exhibiting greater dispersion across the observed units contain more information and thus contribute more to the evaluation process. Conversely, criteria with limited variation among countries possess lower discriminatory power and are assigned smaller weights.

The entropy weighting method is particularly suitable for macro-level comparative analyses, such as cross-country assessments within the European Union, where transparency and objectivity in weighting are essential.

Entropy-based weighting was applied to objectively determine criterion importance based on data variability, following the information entropy concept introduced by Shannon (1948) and its subsequent application in multi-criteria decision-making methods (Wang & Lee, 2007).

3.4 The TOPSIS method

To rank European Union member states by their level of circular economy development, this study applies the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method. TOPSIS is one of the most widely used multi-criteria decision-making techniques for evaluating complex systems, as it enables the ranking of alternatives based on their relative distance from ideal and anti-ideal solutions (Hwang & Yoon, 1981). The core concept of the TOPSIS method is to identify a positive ideal solution, representing the best performance across all criteria, and a negative ideal solution, representing the worst performance. An alternative is considered preferable if it is closer to the ideal solution and further from the anti-ideal solution. This approach provides an intuitive and transparent ranking mechanism in decision-making contexts involving multiple heterogeneous criteria (Hwang & Yoon, 1981).

In this study, the application of the TOPSIS method follows standard procedural steps, including data normalisation, criterion weighting using entropy-derived weights, determination of ideal and anti-ideal solutions according to the predefined MIN/MAX orientation, and calculation of the relative closeness of each alternative to the ideal solution (Hwang & Yoon, 1981). The resulting TOPSIS score serves as a composite indicator of circular economy performance and forms the basis for ranking EU countries.

TOPSIS is particularly suitable for macro-level comparative analyses, such as cross-country assessments within the European Union, due to its clarity, robustness, and ease of interpretation. Its extensive application in circular economy and sustainability studies further supports its appropriateness for the analytical framework adopted in this research. To improve methodological robustness, the TOPSIS-based ranking was additionally compared with rankings obtained under alternative weighting scenarios and normalization procedures. The comparative analysis showed a high degree of ranking stability among the leading and lagging countries, suggesting that the overall conclusions are not driven by a single specification of the TOPSIS model.

3.5 Analysis of digital transformation and ERP system adoption

After ranking EU countries by circular economy performance using the TOPSIS method, the second stage of the analysis investigates the relationship between circular economy performance and enterprise-level digitalisation, with a particular focus on ERP system adoption. The TOPSIS closeness coefficient (Ci^+) serves as the dependent variable, while digitalisation is evaluated through indicators of ERP and ICT usage in enterprises. Additionally, GDP per capita is included as a control variable to account for cross-country differences in economic development. The TOPSIS closeness coefficient (Ci^+), normalized within the [0, 1] interval, is treated as a continuous composite indicator of circular economy performance in the subsequent regression analysis.

The relationship between digitalisation-related variables and circular economy performance is first examined using regression analysis, facilitating an assessment of how much enterprise-level digital technologies contribute to explaining cross-country variation in TOPSIS-based circular economy outcomes across EU member states. This approach aligns with recent macro-level empirical studies that highlight digitalisation is associated with sustainable and circular economic development (Gil-Lamata, 2024; Afolabi, 2025). Furthermore, a group-based comparative analysis is conducted based on the TOPSIS results. EU countries are classified into three distinct groups according to their Ci^+ values using a natural breaks classification (Ju *et al.*, 2025). The natural breaks approach was selected because it enables the identification of relatively homogeneous country groups based on the empirical distribution of the TOPSIS scores, while preserving interpretability within the policy-oriented comparative framework adopted in this study. This classification enables comparison of average digitalisation indicators and TOPSIS scores across the groups, providing additional insights into structural differences in circular economy performance and the role of digitalisation and ERP systems in distinguishing leading, transitional, and lagging countries.

4 RESULTS

To objectively determine the relative importance of circular economy criteria, the entropy method was applied. This approach assigns weights based on the informational content of the data, so criteria with greater variability across countries receive higher weights due to their stronger discriminatory power. The relative importance of the circular economy criteria, as determined by the entropy weighting method, is shown in Figure 1.

The results indicate that patents related to recycling and secondary raw materials carry the greatest weight, highlighting the importance of innovation capacity in differentiating circular economy performance across EU countries. This outcome is expected, as the entropy method assigns greater weight to criteria with higher variability among countries, and innovation activity is a key factor distinguishing circular economy development within the EU. In contrast, indicators such as recycling rates or consumption footprint tend to be more uniform due to shared EU policies, while innovation capacities reflect structural differences in industrial development and investment in research and development. These findings are consistent with recent studies identifying innovation is associated with circular economy development in European countries (European Commission, 2023; Cagno *et al.*, 2025), confirming the methodological and theoretical relevance of applying the entropy method in this context.

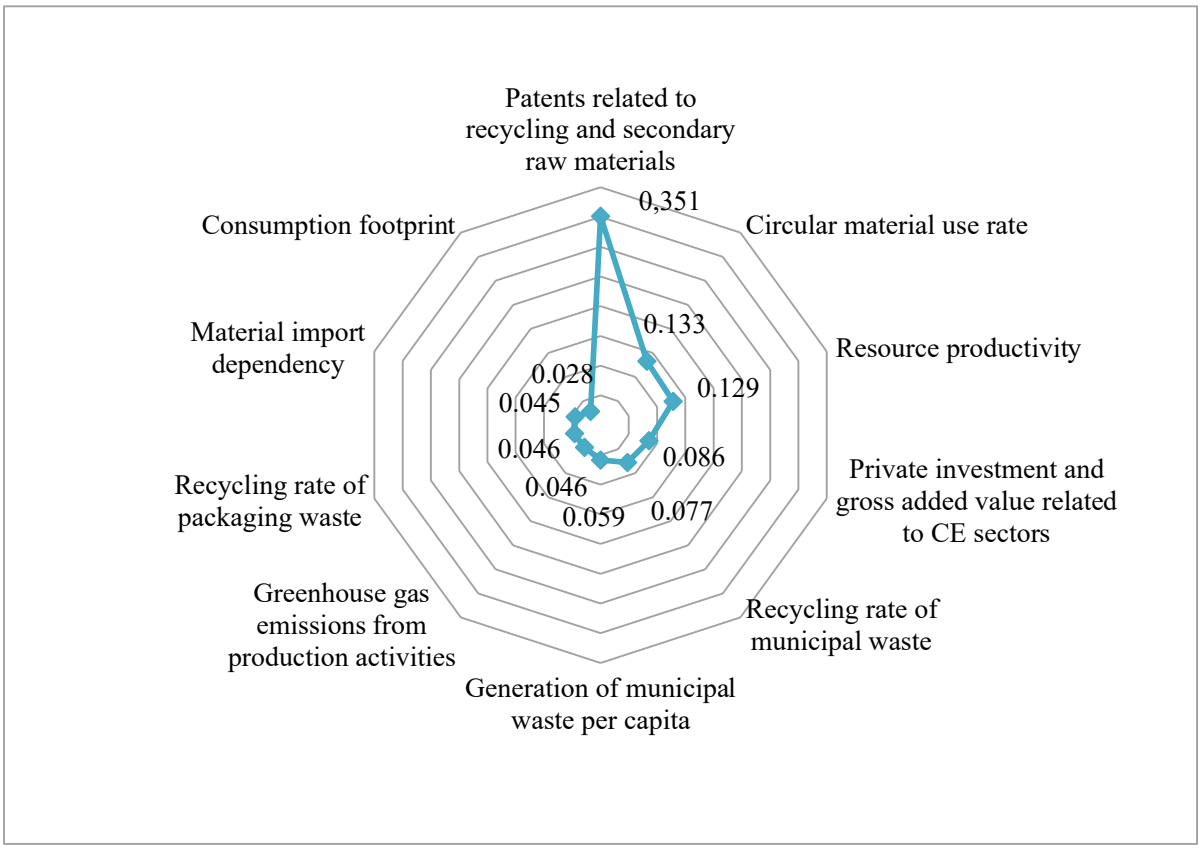

Fig. 1: Entropy-based weights of circular economy criteria

Using the entropy-derived weights and normalised criteria values, the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was used to rank EU countries according to their circular economy performance. The final result is expressed as the closeness coefficient to the ideal solution (Ci+ score), with higher values indicating better performance. The TOPSIS-based ranking of EU countries by circular economy performance is shown in Table 3.

The TOPSIS results reveal significant heterogeneity among EU member states. Countries with strong industrial bases, advanced innovation systems, and well-established circular economy policies rank highest, while those with lower innovation capacity and structural challenges demonstrate weaker circular economy performance. Additional robustness checks confirmed that the relative positions of leading and lagging countries remained largely stable under alternative weighting specifications, indicating that the obtained ranking structure is not highly sensitive to a single TOPSIS configuration.

Figure 2 shows the TOPSIS-based ranking of EU countries by their circular economy performance, measured by the Ci^+ closeness coefficient. Countries are arranged from highest to lowest Ci^+ values, with colour coding reflecting a natural-breaks classification based on the distribution of Ci^+ scores. Specifically, countries with $Ci^+ \geq 0.30$ are classified as circular economy leaders, those with $0.11 \leq Ci^+ < 0.30$ as transitional performers, and countries with $Ci^+ < 0.11$ as lagging performers. This visualisation highlights pronounced structural differences across the three groups, revealing a compact group of high-performing countries, a broad transitional zone, and a homogeneous cluster of low-performing countries situated far from the ideal solution.

Tab. 3 TOPSIS ranking of EU countries by circular economy performance

Country	S^+	S^-	Ci^+	Rank
Belgium	0.21	0.07	0.25	8
Bulgaria	0.26	0.02	0.07	25
Czechia	0.24	0.04	0.14	14
Denmark	0.24	0.04	0.13	15
Germany	0.05	0.25	0.85	1
Estonia	0.25	0.05	0.15	12
Ireland	0.24	0.04	0.13	16
Greece	0.26	0.02	0.07	26
Spain	0.19	0.08	0.29	7
France	0.15	0.11	0.43	4
Croatia	0.26	0.02	0.08	24
Italy	0.13	0.13	0.49	2
Cyprus	0.26	0.02	0.07	27
Latvia	0.26	0.03	0.10	21
Lithuania	0.25	0.02	0.09	23
Luxembourg	0.25	0.06	0.18	10
Hungary	0.25	0.03	0.09	22
Malta	0.25	0.04	0.15	13
Netherlands	0.15	0.13	0.45	3
Austria	0.16	0.11	0.40	5
Poland	0.21	0.05	0.20	9
Portugal	0.24	0.03	0.11	19
Romania	0.23	0.04	0.17	11
Slovenia	0.25	0.03	0.11	20
Slovakia	0.25	0.03	0.11	18
Finland	0.17	0.10	0.38	6
Sweden	0.24	0.03	0.12	17

The clustering analysis revealed the existence of distinct country archetypes within the European Union. The first cluster included highly digitalised and innovation-oriented economies with strong circular economy performance, while the second cluster represented transitional economies characterised by moderate levels of digitalisation and circularity outcomes. The third cluster comprised countries with comparatively low digital readiness and weaker circular economy performance.

Following the ranking procedure, the relationship between enterprise-level digitalisation indicators and circular economy performance was examined. Specifically, ERP usage, ICT usage in enterprises, and GDP per capita (PPP) as a control variable were analysed. Table 4 presents the correlation coefficients between the CE score and the selected explanatory variables.

The results indicate that ERP system adoption has the most consistent association with circular economy performance, particularly when rank-based relationships are considered. ICT usage shows a moderate linear relationship, while GDP per capita plays a significant role in explaining the ranking structure of CE performance across EU countries.

To assess the relative contributions of digital technologies and economic development, a series of multiple linear regression models was estimated. All coefficients are reported as standardised beta values (Table 5), enabling direct comparison of effect sizes.

The regression results confirm that enterprise-level digitalization, particularly ERP and ICT usage, is a key driver of circular economy performance. While GDP per capita is positively related to circular economy performance at the ranking level, its direct effect becomes statistically negligible once digital variables are introduced, suggesting that digital transformation partially mediates the impact of economic development.

Tab. 4 Correlation between CE score and explanatory variables

Variable	Pearson r	Spearman ρ
ERP usage	0.341	0.433
ICT usage in enterprises	0.362	0.154
GDP per capita (PPP)	0.234	0.493

Tab. 5 Regression results (standardized β coefficients)

Model	ERP usage	ICT usage	GDP per capita	R^2
Model 1: CE ~ ERP	0.341	–	–	0.116
Model 2: CE ~ ERP + ICT	0.374	0.394	–	0.270
Model 3: CE ~ ERP + ICT + GDPpc	0.349	0.393	0.046	0.272

5 DISCUSSION

In recent years, there has been increased focus on developing the circular economy across the European Union, particularly regarding sustainability, resource efficiency, and long-term economic resilience (European Commission, 2023). Despite growing policy efforts and academic interest, significant differences in circular economy performance persist among EU member states, raising questions about the structural and technological factors underlying these disparities.

The findings of this study largely align with previous research on the development of the circular economy at the EU level, while also providing methodological and empirical improvements. Studies employing multi-criteria decision-making approaches to rank countries, such as Ūsas *et al.* (2025), Grybaitė and Burinskienė (2024), and earlier researchs (Mardani *et al.*, 2018; Zavadskas *et al.*, 2016), consistently show notable differences in circular economy development among EU member states, with more industrialised and innovation-focused countries frequently leading. These conclusions are fully consistent with this study's results, which identify Germany, Italy, the Netherlands, France, Austria, and Finland as top performers based on the TOPSIS ranking. Germany's leading position can be directly attributed to its high scores on innovation-related indicators, which, according to the entropy analysis, have the greatest impact on the final ranking. This finding is in line with previous studies showing that countries with robust industrial foundations, well-developed innovation systems, and long-term sustainability policies tend to achieve better circular economy outcomes (Mohajan, 2021; Grybaitė & Burinskienė, 2019). Conversely, countries at the lower end of the ranking (Cyprus, Greece, Bulgaria, Croatia, Lithuania, Hungary) consistently record lower scores across most criteria, especially in innovation, resource productivity, and waste management, indicating the presence of structural constraints that impede their transition towards a circular economy model. The classification of EU countries into leader, transitional, and lagging clusters highlights that differences in circular economy performance stem primarily from structural capacities and innovation readiness rather than from marginal variations in individual indicators.

However, unlike most of the studies mentioned, which focus solely on circular economy indicators and their relative significance, this research also examines the role of enterprise-level digitalisation in explaining cross-country differences in circular economy performance. Conceptual studies highlighting the importance of ERP systems in supporting sustainable and circular business practices (Abobakr *et al.*, 2025; Anjaria, 2025) provide a theoretical basis for selecting ERP and ICT variables in this study, while macro-level empirical analyses confirm that digitalisation is associated with progress in the circular economy (Afolabi, 2025; Gil-Lamata, 2024). In this context, the results of regression analysis indicate that ERP usage and ICT adoption are positively associated with circular economy performance, while including GDP per capita as a control variable does not significantly alter these relationships. This finding suggests that the digitalisation variables explain a substantial share of cross-country variation on differences in circular economy performance than the overall level of economic development. By selecting ERP and ICT variables, the analysis focuses on specific digital practices within companies that directly influence resource planning, material flow management, and the coordination of circular activities. These findings are consistent with recent studies emphasising digital technologies as key enablers of circular business models and enhanced resource efficiency (Neri *et al.*, 2023; Cagno *et al.*, 2025), while also suggesting that economic wealth alone is insufficient for achieving high circular economy performance. Accordingly, this study not only confirms existing evidence on the heterogeneity of circular economy development within the EU, but also advances previous research by combining multi-criteria ranking methods with enterprise-level digitalisation analysis in a single analytical framework.

This study contributes to the literature on circular economy development in the European Union in several important ways. First, it advances previous research by integrating a multi-criteria decision-making approach with an empirical analysis of enterprise-level digitalisation, moving beyond studies that focus solely on circular economy indicators and their relative importance. By combining TOPSIS-based country ranking with regression and group-based comparative analyses, the study provides a more comprehensive framework for understanding cross-country variations in circular economy performance. Second, the findings provide new empirical evidence on the role of operational digital readiness, demonstrating that ERP system usage and ICT adoption are linked with circular economy performance, even after controlling for economic development. This result refines existing insights by showing that digitalisation contributes independently to circular economy outcomes, rather than merely reflecting broader economic conditions. Third, the study shows that digital technologies, while important, are not sufficient on their own to ensure high circular economy performance. The identified leader, transitional, and lagging country clusters reveal that structural capacities and innovation readiness play a decisive role in shaping circular economy outcomes. In this way, the research deepens theoretical understanding of the interaction between digitalisation, innovation systems, and structural conditions in the transition towards a circular economy.

6 CONCLUSION

The integration of digital transformation processes into circular economy strategies has become an increasingly important issue in both academic research and policy discussions within the European Union. Hence, this study examined the relationship between circular economy performance and enterprise-level digitalisation in the European Union, with particular emphasis on the role of ERP systems. Using a two-phase methodological approach, the research combined a TOPSIS-based composite index and country ranking with regression and group-based comparative analyses to explore the drivers of cross-country differences in circular economy outcomes.

The results confirm substantial heterogeneity in circular economy performance across EU member states, with innovation-oriented and industrially advanced countries consistently achieving higher rankings. At the same time, the findings demonstrate that enterprise-level digitalisation, including ERP system usage and ICT adoption, is positively and significantly associated with circular economy performance. Importantly, these effects persist even when differences in economic development are taken into account, indicating that digitalisation of business processes plays a more decisive role than overall economic wealth alone. However, the analysis also shows that digital technologies are not sufficient by themselves to ensure high levels of circular economy performance. Countries that perform best combine digital readiness with strong structural and innovation capacities, while lagging countries face persistent constraints related to innovation, resource productivity, and waste management systems. In addition to its analytical contribution, the proposed composite CE index may serve as a policy-oriented benchmarking and monitoring tool for assessing cross-country differences in circular economy progress and digital readiness within the European Union.

Although the results offer significant insights into the connections between circular economy performance and digitisation in EU member states, the research has several limitations. The analysis relies on aggregated country-level data, which does not capture the heterogeneity of sectors and enterprises. Future research should extend the present macro-level approach by

integrating firm-level ERP log data and operational sustainability indicators in order to examine how granular resource-flow monitoring and digital process integration relate to circular economy outcomes within organisations. In this sense, the present study may serve as an initial macro-level step toward more detailed micro-level investigations of digital-enabled circular economy practices. The methodological framework, based on a combination of the entropy method and TOPSIS, could be extended by applying alternative or hybrid MCDM methods, such as PROMETHEE, VIKOR, or hybrid MCDM models, to assess the robustness and stability of the obtained rankings. Future studies could further strengthen the comparative analysis by applying clustering techniques such as k-means clustering combined with silhouette coefficient validation in order to identify more refined archetypes of digitalisation and circular economy performance across EU countries. Additionally, the set of indicators could be further expanded to include institutional frameworks, regulatory policies, and innovation capacities, enabling a more comprehensive assessment of circular economy development.

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