

COST Action CA22124 – ECO4ALL

SPECIAL ISSUE



ECO4ALL
EU Circular Economy Network for All
Consumer Protection through reducing, reusing, repairing



CONSUMER RIGHTS IN THE AGE OF THE CIRCULAR ECONOMY: TOWARDS SUSTAINABLE AND FAIR PRODUCTION AND CONSUMPTION PRACTICES



“CONSUMER RIGHTS IN THE AGE OF THE CIRCULAR ECONOMY: TOWARDS
SUSTAINABLE AND FAIR PRODUCTION AND CONSUMPTION PRACTICES”

– COST Action CA22124 ECO4ALL –
SPECIAL ISSUE



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Special Issue Book

“Consumer Rights in the Age of the Circular Economy: Towards Sustainable and Fair Production and Consumption Practices”

Achieving sustainable and fair production and consumption has become a collective priority in contemporary societies. However, significant regional disparities persist both within the European Union and globally, affecting the capacity of countries, organisations, and consumers to engage effectively in the transition towards more sustainable economic models. In this context, the circular economy (CE) represents a key paradigm for promoting responsible production, sustainable consumption, resource efficiency, and consumer protection.

COST Action CA22124 ECO4ALL, “*EU Circular Economy Network for All: Consumer Protection through Reducing, Reusing, Repairing*”, addresses these challenges by fostering international and interdisciplinary cooperation and promoting a consumer-centred approach to circularity. In particular, ECO4ALL emphasises the importance of considering consumers not merely as recipients of products and services, but as active participants in circular systems, while also recognising the responsibility of producers, institutions, and other stakeholders in creating the conditions for sustainable and fair consumption.

This Special Issue was developed within the framework of the International ECO4ALL Conference 26-27 March, 2026, “*Consumer Rights in the Age of the Circular Economy: Towards Sustainable and Fair Production and Consumption Practices*”, organised in Rome at Mercatorum University, Italy. It builds on the scientific exchange fostered by the conference and brings together selected contributions representing some of the key themes addressed during the event.

The Special Issue explores the transition towards circular economic systems from different but complementary perspectives, focusing particularly on the relationships between circular economy practices, sustainable production and consumption, and consumer interests. The selected contributions address key dimensions of this transition, including sustainable resource management, product lifecycle extension through reducing, reusing, and repairing, consumer behaviour and sustainable consumption, policy and institutional frameworks, socio-economic implications of circularity, and the conditions that facilitate or hinder the adoption of circular practices.

By bringing together different disciplinary, geographical, and methodological perspectives, the Special Issue highlights the multifaceted nature of the transition towards a circular economy. The contributions of this Special Issue demonstrate that circularity cannot be understood exclusively in terms of resource efficiency or environmental impact reduction. Rather, it represents a broader socio-economic transformation that requires the involvement of multiple actors and the integration of environmental sustainability, economic viability, social fairness, and consumer protection. In this way, the Special Issue contributes to the ongoing academic and policy debate by advancing a more integrated and consumer-centred understanding of the circular economy and by providing insights into how circular principles can be translated into sustainable, fair, and context-sensitive practices across different institutional, market, and geographical settings.

The Special Issue therefore represents one of the scientific outcomes of the ECO4ALL International Conference 2026, and it is based upon work from COST Action CA22124 - ECO4ALL “EU Circular Economy Network for All: Consumer Protection through reducing, reusing, repairing”, supported by COST (European Cooperation in Science and Technology - www.cost.eu).

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CONSUMER PROTECTION AND THE LONGEVITY OF NANOMATERIALS BLENDED ULTRAFILTRATION MEMBRANES FOR CIRCULAR WATER SYSTEMS

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Abstract

The development of closed loop water system technology, which is treated water is continuously recycled within a defined system boundary, requires advanced treatment methods guaranteeing high quality treated water. Polymeric ultrafiltration membranes are widely used for water recovery. Nevertheless, their lifespan is often restricted by fouling. In this paper, nanomaterials blended ultrafiltration membranes incorporating nano sized zinc oxide (ZnO NP) and multi walled carbon nanotubes (MWCNT) were comparatively examined regarding their suitability for closed loop water systems from performance and consumer protection points of view.

The incorporation of 1 wt% ZnO NP increased flux from 54 to 58 L m⁻² h⁻¹, and solute rejection from 81% to 86%. However, it did not significantly affect the porosity and hydraulic resistance. On the other hand, the addition of 1 wt% MWCNT resulted in an increase in flux from 29 to 107 L m⁻² h⁻¹, and improved rejection from 45% to 80%. The hydraulic resistance decreased from 13×10^{12} to 11×10^{12} m⁻¹. These results suggest performance enhancement by improving pore structure with ZnO NP, and by pore connectivity with MWCNT. From the perspective of consumer protection, both nanomaterial systems show improved properties which can lead to better efficiency and reliability in terms of wastewater reuse process. Especially reduced hydraulic resistance of the MWCNT modified membrane may offer additional operational advantages.

Key words: MWCNT, ZnO NP, ultrafiltration, consumer protection, nanomaterials, water treatment

Introduction

Membranes are extensively used in water and wastewater treatment as well as industries such as food, petrochemical, and energy (Daufin et al., 2001, Ravanchi et al., 2009, Wang et al., 2011, Li et al., 2011, Lee et al., 2014). Membrane technologies are low cost and more energy efficient than other water treatment techniques (Nasrollahi et al., 2018, Aziz et al., 2024).

Ultrafiltration can be considered as a porous membrane with a pore size of typically ranging from 0.001 to 0.1 µm (Mulder, 1997). Ultrafiltration membranes often have an anisotropic structure, having a dense layer on top of a microporous layer. The separation process is carried out in the dense layer, and mechanical strength is provided by the

microporous layer (Baker, 2004). Small, suspended particles and dissolved macromolecules pass through the ultrafiltration membrane, while larger molecules are mainly rejected (Idris et al. 2006).

Polymeric membranes are flexible, tough, economical, and have good separation properties, but their mechanical, thermal, and chemical resistance are low (Peng et al., 2007, Mollahosseini et al., 2025). In addition, fouling problem is one of the most significant disadvantages of membrane technology (Nguyen et al., 2012, Balta et al., 2012). The reduction in the separation performance of a membrane is referred to as membrane fouling. When a membrane becomes fouled, the amount of permeate obtained decreases (Koyuncu, 2018). Colloids, particles, macromolecules, salts, and similar substances accumulate within the membrane pores and/or on the membrane surface, causing fouling (Geise et al., 2010). Membrane fouling is divided into reversible and irreversible fouling. Reversible fouling can be removed by hydraulic cleaning methods. However, irreversible fouling is eliminated by cleaning the membrane with chemical solutions. The use of chemicals shortens membrane lifetime (Meng et al., 2009).

Studies have shown that increasing membrane hydrophilicity reduces membrane fouling by decreasing hydrophobic interactions between foulants and the membrane surface (Gohari et al., 2014, Damodar et al., 2009, Leo et al., 2012). Therefore, in recent years, the production of low cost polymeric membranes with high fouling resistance have attracted significant attention. There are three main methods to increase membrane hydrophilicity. These methods are blending the polymer with another hydrophilic material, grafting the polymer with hydrophilic monomers or functional groups, and coating the membrane with a hydrophilic material (Celik Madenli et al., 2017).

Nanoparticles such as aluminium oxides (γ -Al₂O₃, α -Al₂O₃), zirconium oxide (ZrO₂), titanium oxide (TiO₂), cerium oxide (CeO₂), silicon dioxide (glass) (SiO₂), and zinc oxide (ZnO), are widely used as additives for membrane synthesis (Aksu, 2019, Koyuncu, 2018). It was shown in literature that TiO₂ nanoparticles are very effective for fouling control (Rahimpour et al., 2011, Bae et al., 2006). However, ZnO NP is an excellent alternative to TiO₂ nanoparticles for fouling control due their high surface to volume ratio and low cost. It was shown that ZnO NP addition increases membrane hydrophilicity and permeate flux (Ahmad et al., 2018, Celik Madenli et al., 2023). Multi walled carbon nanotubes (MWCNT) are also attractive nanomaterial with exceptionally high aspect ratio, strength and stiffness (Gojny et al., 2004). It was shown that CNT blended membranes are more hydrophilic, with a higher flux (Celik et al., 2011a, Celik et al., 2011b).

The use of nanomaterials for membrane preparation has significant implications for consumer protection and environmental sustainability. The challenges include nanoparticle release into treated water, stability of nanoparticle blended membranes. The treated water is reused for domestic and industrial purposes in circular systems. Hence ensuring consumer protection and regulatory compliance is as important as achieving high technical performance. Therefore, this study aims to assess the performance, longevity, and consumer protection effects for the MWCNT, and ZnO NP blended membranes.

Membrane Preparation and Characterisation

Membranes were synthesized based on the nanoparticle doped membrane synthesis method through phase inversion method as described in the literature (Celik et al 2011a, Celik et al. 2011b, Celik and Choi 2011, Celik Madenli and Ciftci 2022, Celik Madenli et al. 2023). In membrane synthesis, ZnO NP or MWCNT were used as additives, and N-methyl-2-

pyrrolidone (NMP) or N,N-Dimethylformamide (DMF) were used as solvents. Before use MWCNT were functionalized in an acid mixture, as described elsewhere (Celik et al. 2011a, Celik et al. 2011b, Celik Madenli et al. 2017, Celik Madenli et al. 2021, Celik Madenli and Cakmakci 2017, Celik Madenli and Ciftci 2022, Celik Madenli and Kesiktas, 2023). During the synthesis, nanoparticles were first added to the solvent. Then, polyethersulfone was added to obtain the membrane solution. The obtained membrane solution was poured onto a glass plate using an automatic film applicator. Membranes were formed by placing the glass plate into a coagulation bath. The prepared membranes were washed with and stored in distilled water until use. Compositions of the membranes prepared are presented in Table 1.

Table 1. Composition of membranes

<i>Membranes</i>	<i>Polyethersulfone Ratio</i>	<i>nZnO Ratio</i>	<i>CNT Ratio</i>	<i>NMP Ratio</i>	<i>DMF Ratio</i>
<i>0 wt% ZnO NP</i>	15	0	0	85	0
<i>1 wt% ZnO NP</i>	15	1	0	85	0
<i>0 wt% MWCNT</i>	15	0	0	8.5	76.5
<i>1 wt% MWCNT</i>	15	0	1	8.5	76.5

The porosity (ε) of the membranes was determined by measuring the dry (w_d , g) and wet weights (w_w , g) of the membranes by using the following equation.

$$\varepsilon = (w_w - w_d) / (\rho \times A \times h).$$

where A represents the membrane area (cm^2), h represents the membrane thickness (cm), and ρ represents the density of pure water. For each membrane, the mean and standard deviation were determined based on at least two independent measurements

Contact angle measurement was performed using the sessile drop technique by using a contact angle goniometer. A drop of pure water (1 μL) was placed on the membrane surface, and a measurement was taken. To minimise experimental error, at least five replicate measurements were conducted for each sample, and the results are reported as the mean and standard deviation.

Membrane filtration tests were conducted by using a crossflow membrane filtration unit for ZnO NP blended membranes and dead-end membrane filtration unit for MWCNT blended membranes. 0.5 bar of constant transmembrane pressure was applied during permeability and selectivity tests. The water flux (J_w , $\text{L}/\text{m}^2\text{h}$) was determined using the following equation.

$$J_w = V / (A \times \Delta t)$$

where V represents the volume of the permeate (L), and Δt represents time (h).

One of the typical pollutants found in water treatment is protein-like substances that cause serious fouling during membrane filtration (Liu et al. 2013, Ding et al. 2019, Huner et al 2017, Vanangarnudi et al. 2017). In this study, bovine serum albumin was used as a model protein. Bovine serum albumin filtration for 1 hour was performed to examine the selectivity and fouling resistance. Bovine serum albumin rejection ratio (R , %) and hydraulic resistance of the membranes (R_m , m^{-1}) were determined by using the following equations.

$$R = (C_f - C_p) / C_f$$

$$R_m = \Delta P / (\mu \times J_p)$$

where μ represents water viscosity, ΔP represents transmembrane pressure (Pa), and J_p represents the protein filtration flux ($\text{L}/\text{m}^2\text{h}$).

Results and Discussion

Nanomaterial Incorporation Effects on Membrane Structure

The addition of nanomaterials in ultrafiltration membranes had significant effects on the structure and properties of the membranes, reflected by changes in porosity, contact angle, bovine serum albumin rejection, and hydraulic resistance, as shown in Table 2. These effects are strongly dependent on the type of nanomaterial used. Hence, additive selection is very critical when designing membranes for circular water systems.

Table 2. Properties of the membranes

<i>Membranes</i>	ε	<i>Contact Angle (°)</i>	$R_m (m^{-1})$
<i>0 wt% ZnO NP</i>	0.43	66	17×10^8
<i>1 wt% ZnO NP</i>	0.43	64	17×10^8
<i>0 wt% MWCNT</i>	0.25	67	13×10^{12}
<i>1 wt% MWCNT</i>	0.29	62	11×10^{12}

For the ZnO NP blended membranes, addition of 1 wt% ZnO NP led to a decrease in contact angle from 66° to 64°. Reduced contact angle shows increased hydrophilicity. This increase in hydrophilicity is likely due to the hydrophilic nature of ZnO NP, which promotes faster solvent and nonsolvent exchange during phase inversion and may contribute to formation of a more interconnected pore structure. An increase in hydraulic resistance indicates an increase in fouling. The unchanged hydraulic resistance suggests ZnO NP addition in blended membranes did not significantly alter the fouling behaviour.

For the MWCNT blended membranes, addition of 1 wt% MWCNT resulted in an increase in membrane porosity from 0.27 to 0.32. The reduction in hydraulic resistance from 13×10^{12} to $11 \times 10^{12} m^{-1}$ suggests increasing fouling resistance of the MWCNT blended membranes. In addition, contact angle reduced from 66° to 64° shows increased hydrophilicity.

Permeability and Rejection Performance

While permeability enhancements are desired to reduce energy consumption in circular water systems, sufficient solute rejection is crucial in terms of consumer protection. In ZnO NP blended membranes, 1 wt% ZnO NP addition increased the rejection from 81% to 86%, together with an increase in flux from 54 to 58 L/m²h (Figure 1). Such simultaneous improvement suggests that ZnO NP may have enhanced pore size distribution uniformity and/or surface interactions with the rejected solute, thus offsetting the effect of increased porosity.

A different trend was observed for the MWCNT blended membranes. The flux increased, from 29 to 107 L/m²h. This considerable improvement in permeability was accompanied by a significant improvement in rejection, which increased from 45% to 80% with 1 wt% MWCNT addition. This implies that MWCNT incorporation not only enhanced hydraulic performance but also contributed to a more controlled pore structure, probably because of reduction in macrovoids or reinforcement of the polymer matrix. Improvement in rejection with increased permeability points out the ability of MWCNT to favorably overcome the commonly confronted permeability-selectivity trade-off in polymeric membranes.

When high flux and high removal are achieved simultaneously during membrane filtration, concentration polarization occurs due to the accumulation of rejected solutes near the membrane surface. Therefore, controlling concentration polarization is important in ultrafiltration processes (Celik and Choi 2011, Vankelecom et al., 2005).

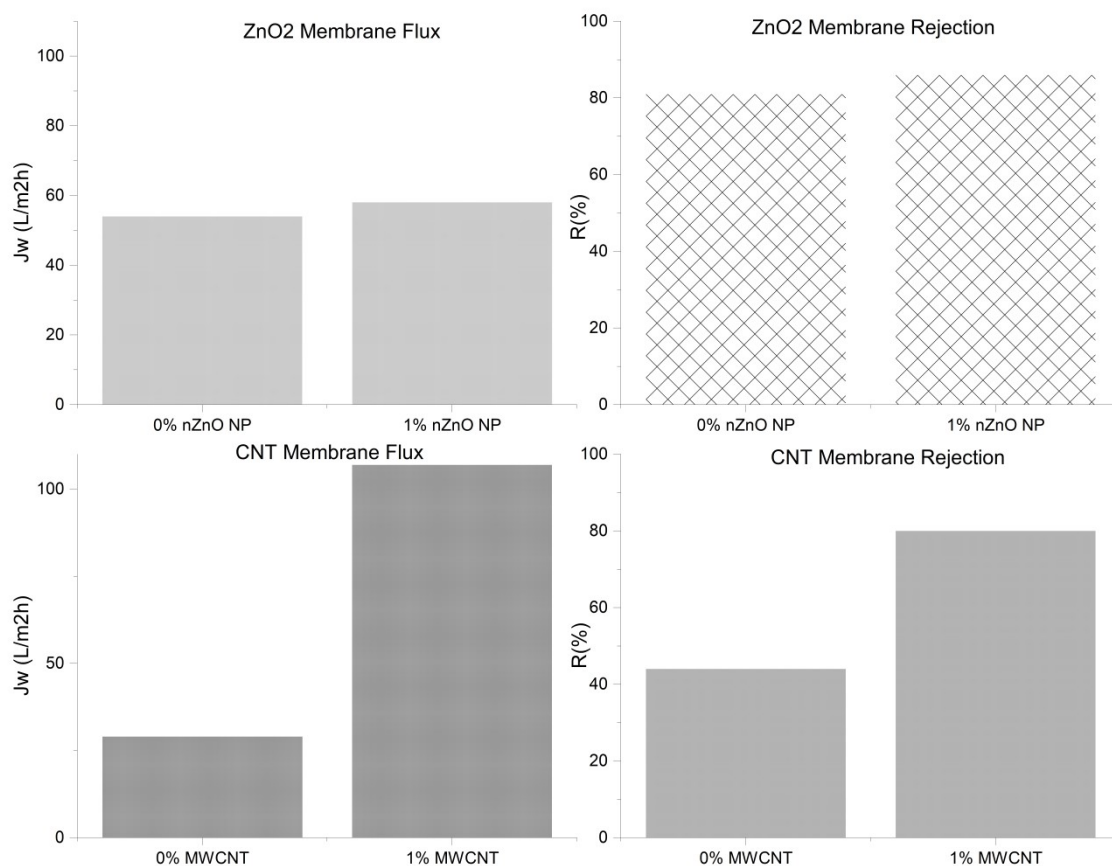


Figure 1. Flux and rejection of the nanomaterials blended membranes

Membrane Longevity and Operational Stability

Membrane longevity is closely related to hydraulic resistance, structural integrity, and fouling tendency. A decrease in the hydraulic resistance upon the addition of MWCNT indicates improved water transport characteristics during pressure driven operation. Lower hydraulic resistance also points toward a reduction of energy consumption and lessened mechanical stress during prolonged filtration cycles. On the other hand, the hydraulic resistance values were in the order of 10^{12} m^{-1} for the MWCNT blended membranes, which is significantly higher than that of the ZnO NP blended membranes, which were of the order of 10^8 m^{-1} . This represents a distinct difference between the pore structures of the membranes.

Consumer Protection

From the perspective of consumer protection, these two nanomaterials have different advantages and challenges. ZnO NP possesses higher rejection, which is favourable for water reuse. While the case for ZnO NP is based on strong material immobilization, that of MWCNT relies on strong material embedding within the polymer matrix. The strong enhancement of permeability achieved with low additive load, alongside high rejection,

indicates that MWCNT have strong potential for delivering strong performance with minimal additive content.

From a consumer protection and regulatory law perspective, the use of nanomaterials in ultrafiltration membranes for water treatment engages a clear framework of rights and obligations applicable to all actors involved in the water supply chain. Consumers have a fundamental right to have access to safe, clean, and legally compliant water, as this right is firmly included in EU Drinking Water Directive (EU) 2020/2184. In turn, the manufacturers of filtration membranes, water utilities and system operators face legal obligations to ensure that innovative materials, including nanomaterials, do not impair water quality over their intended lifetime. This encompasses activities such as carrying out appropriate risk assessments, avoiding accidental release of nanoparticles, and ensuring long-term material performance in line with public health protection requirements. Membrane longevity, in this regard, is not only a technical benefit but also a legal safeguard toward continued regulatory compliance and customer confidence.

In parallel, the product safety and chemical regulation framework also lays down obligations for diligence, transparency, and accountability for economic operators in the market with regard to the placing of nanomaterial-based products. The European General Product Safety Framework and the REACH Regulation hold the manufacturer liable for the safety of the materials used by the manufacturer, including the traceability and performance of the water supplier. Failure to comply with such obligations may give rise to regulatory enforcement or liability claims, particularly where damage to consumer health or the environment is claimed. Legal design considerations for ultrafiltration membranes with durability, stability, and safety-by-design principles, therefore, represent a direct legal underpinning for the fulfilment of such obligations and reinforce consumers' rights to informed, safe, and sustainable water services in circular water systems.

Relevance to Circular Water Systems

In the case of circular water systems, membranes must be able to perform for longer durations, and in the process, they also need to ensure the quality of the water that is produced. The results show that the role of ZnO NP and MWCNT in the membranes brings about an improvement in the performance of the membranes compared to their pristine form, but in different ways. While the role of ZnO NP brings about an ideal balance between the permeability and rejection properties of the membrane, the role of MWCNT achieves greater permeability efficiency with higher selectivity. Thus, the role of nanomaterials in membranes needs to be assessed in an integral way, taking into consideration performance parameters, as well as longevity and consumer protection.

Limitations

MWCNT leaching during membrane filtration was evaluated using UV–Vis spectroscopy based on Beer–Lambert’s law at 810 nm in deionised water. No MWCNTs were detected in either the permeate or retentate streams. Hence, MWCNT release was either below the detection limit or negligible under the experimental conditions. In contrast, although ZnO NP is widely reported in the literature as a low-toxicity nanomaterial, its leaching behaviour was not measured in this study. The systematic assessments of ZnO NP leaching in membrane systems remain limited.

In this study all membranes were prepared and tested at the laboratory scale. Hence, scaling up to pilot or industrial scale may introduce challenges such as homogeneous distribution of nanomaterials, reproducibility, and stability under actual process conditions.

To evaluate nanomaterial blended membranes for regulatory purposes, especially for water treatment, it is important to conduct standard tests for ecotoxicity and safety, which are not within the scope of this research and should be addressed in future research.

Conclusions

This study comparatively analysed nanomaterials blended ultrafiltration membranes using ZnO NP and MWCNT, regarding the performance, durability, and consumer protection within the scope of the circular water management. The findings indicate a significant improvement in membrane properties with the addition of nanomaterials. However, the nature of the impact is different depending on the nanomaterials used.

ZnO NP blending caused a moderate increase in the porosity and permeability of the membranes but at the same time provided enhanced rejection of solutes. Such desirable properties of ZnO NP, confer advantages to ZnO NP blended membranes in applications where water quality assurance are of high priority. However, there is a need to evaluate the stability of the ZnO NP blended membranes and the potential release of ZnO NP to ensure consumer safety in water reuse.

The MWCNT incorporation led to a significant increase in the permeability of the membranes as well as an improved solute rejection and lower hydraulic resistance. The significant level of permeability enhancement obtained at a relatively low MWCNT content confirms effective water transport channels and high interconnectivity without the sacrifices in selectivity. These factors suggest that MWCNT blended membranes can be used in energy efficient environments without sacrificing long-term performance in circular water management. In conclusion, the results demonstrate that nanomaterials blended ultrafiltration membranes are useful in overcoming the limitations of traditional membranes.

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A MIND MAP OF FACTORS INFLUENCING THE CHOICE OF ECO-FRIENDLY AND SUSTAINABLE PRODUCTS: INSIGHTS FROM NEUROMARKETING

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Abstract

Neuromarketing evaluates human expressions to understand people's behavior, and marketing can exploit the main factors associated with each behavior to help individuals make more conscious and environmentally friendly decisions. The decision-making process is complex, but through emotional responses to experiences (products or advertisements), communication can be more assertive if it considers consumer perception.

Attractive eco-friendly packaging and messaging, innovative design, and consumer-centred marketing strategies can influence the decision to purchase eco-friendly and sustainable products, especially when they take into account the level of awareness of perceived value among consumers and buyers. Despite considerations (rational, emotional, and associated risks), can people see the same product differently? To answer this question, the objective of this research was defined: to develop a comprehensive understanding of the factors that influence the consumer decision-making process. On November 27, 2025, this research develops a literature review in Web of Science Core Collection, searching article related to Neuromarketing, to understand the decision-making process of consumption, which can be applied to the eco-friendly and sustainable products campaign. The results structured the factors into five dimensions, and a map mind emerges from it.

Key words: *Consumer behaviour, Neuromarketing, Sustainability, Circular Economy, Social Marketing.*

Introduction

The human face offers a huge amount of information, especially through the expression of emotions (Landmann, 2023). There are multiple factors influencing decision-making process

(Cherubino et al., 2017). The emotional response to experiences (products or advertisements) (Hou et al., 2016) can help in assertive communication. It is an opportunity to improve the campaign based on the consumer's perception. Packages and ecological attractive messages (Ščepková & Zaušková, 2024) and visual design of the eco-product (Ščepková & Zaušková, 2024), could be associated with innovative design and marketing strategies can lead to consumer-centric approach (Sadikzade et al., 2024). Finally, this research defened that marketing strategies and related advertising favour a better perception of value (Al-Kwif, 2016).

Despite considerations (rational, emotional, and associated risks), can people see the same product differently? To answer this question, the objective of this research was defined: to develop a comprehensive understanding of the factors that influence the consumer decision-making process. Neuromarketing is an area of marketing that uses neuroscience (combining psychology and neuroscience) to understand how consumers' brains work. It aims to understand individuals' responses to advertisements and products. It uses tools such as fMRI, EEG, and eye tracking to measure consumers' subconscious behavior.

Assuming that Neuromarketing is the best option to help people to decide, the main objective of marketing is to use these insights to optimize communication strategies to influence the purchasing and consumption decision-making process. In this sense, this article developed a literature review to understand the decision-making process of consumption, which can be applied to the which can be applied to the eco-friendly and sustainable products campaign. On November 27, 2025, this research develops a literature review in Web of Science Core Collection, searching article related to Neuromarketing.

The results structured the factors into five dimensions: rational factors, emotional factors (which are widely used in marketing campaigns), factors associated with risk reduction, as well as raising awareness about individual perception of the decision-making process and its consequences, and the tools that marketing uses and that can also influence the decision. A mind map emerged from the literature review.

Insights from neuromarketing¹ to consumer behavior

Neuromarketing techniques use tools from neuroscience, such as EEG, fMRI, eye tracking, and facial coding, to measure consumers' unconscious responses to marketing stimuli, thereby providing deeper insights than conventional methods. The literature review drew on these studies to present a mental map of the factors that influence decision-making.

Conscious and unconscious mental processes (Cenizo, 2025) can be assessed by neuromarketing, namely through pupil dilation and constriction, including for AI training (McInnes & Sung, 2025).

Rational factors (Piazza et al., 2018; Ferruz-González et al., 2023; Barquero-Pérez et al., 2020; Kaklauskas et al., 2019) may be relevant to certain segments and markets. It plays a stronger role when the effort required is more significant (Kaklauskas et al., 2019). However, most consumer decisions are not determined solely by conscious and rational factors (Ferruz-González et al., 2023; Barquero-Pérez et al., 2020; Piazza et al., 2018).

Based on their feelings and emotional factors (Ferreira et al., 2024; Polo et al., 2024; Aricò et al., 2018), consumer makes more impulsive decisions. Emotions can come up (Kaklauskas et al., 2020) unconsciously (Landmann, 2023), and emotional appeals improve communications, as well as retain attention and increase trust (Russo et al., 2023). Furthermore, emotions, values and ethical preferences (Lytvyn et al., 2023) influence

¹ Neuromarketing (Topic) and rational factor (Topic) in Web of Science Core Collection | Session: November 27, 2025

decision-making process of consumption. More sustainable food choices, for example, can be better analyzed by neuromarketing if it considers sensorial perception experience (Sadikzade et al., 2024; Cherubino et al., 2017). In addition, improvements in labelling and packaging lead to a more favorable response from consumers (Agudelo et al., 2022). A unique experience of consumption, providing competitive advantage (Cuns te al., 2019). To increase effectiveness, affectivity, and emotional understanding would be better (Zavadskas et al., 2019).

Aiming to evaluate attention levels and improve engagement, Guerrero-Pérez et al. (2025) highlighted the design of emotional content should be prioritized in creative processes to increase the sensitivity of the audience. Emotion, perception, connection, affection are fundamental aspects to understand reactions to marketing stimuli (Pavličić, 2025). Social advertising that aims to improve the well-being of individuals and society, combined with disinterested communication, was found to be effective in eliciting emotional responses (Zito et al., 2021). Campaigns with humor and emotion can encourage consumer identification, especially when addressing current issues, fostering a sense of community (Micu et al., 2021). Social media increasingly emphasizes emotional reactions triggered by observing public comments (Ščepková & Zaušková, 2024), and interface layouts should be used to attract user attention (Wang et al., 2021). People consider listening to music relevant. (Leeuwis et al., 2021). According to the authors, music is a meaningful indicator of public judgment.

Additionally, Artificial Intelligence (AI) technologies can analyse data and extract information from it (Beyari et al., 2024), and its tools can be used to understand emotions (Grájeda et al., 2024), as well as its cognitive aspects (Pavličić, 2025) associated to the consumer experience. This review also highlights that the attractiveness of attention and the impact on emotions of stories presented on Instagram depend on gender (Fondevila et al., 2020).

Finally, any marketing campaign, including social marketing campaign, could elicit emotions (Ferruz-González et al., 2023; Piazza et al., 2018), raise awareness (Ferruz-González et al., 2023) and improve consumers perception (Ferruz-González et al., 2023). Negative comments generate doubt and frustration, while positive reviews may serve as social proof (Ščepková & Zaušková, 2024). memorization can be enhanced by appealing, interactive and immersive visualizations (Beyari et al., 2024). Combining image and sound stimulation led to better performance regarding consumer choices (Polo et al., 2024). Marketing should provide confidence to the customer by ensuring risk reduction.

Methodology and equation research

On November 27, 2025, this research develops a literature review in Web of Science Core Collection, searching for these equations: (i) Neuromarketing (Topic) and rational factor (Topic), which result in four articles; (ii) Neuromarketing (Topic) and emotional factors (Topic), which result in thirty articles. The objective of this research was defined: to develop a comprehensive understanding of the factors that influence the consumer decision-making process, to offer a way to be applied to each consumer's behavior.

Based on a review of the literature, five theoretical dimensions of factors influencing consumer decisions were identified, three of which are associated with neuromarketing: i) rational factors, which follow decision-making processes justified by concrete grounds; ii) emotional factors, which follow decision-making processes justified by grounds associated with emotion and affection; i) factors that aim to reduce or control risk, and follow decision-making processes justified by acceptable risks. Two other dimensions were also considered that can amplify the impact of these dimensions on the decision-making process, namely: iv)

awareness of the antecedents and consequences of the decision, which deepen the process; and v) tools, particularly those associated with the communication process, which influence the decision-making process. In this sense, table 1 summarizes these variables and respective indicators that can influence the decision-making process of consumption.

Table 1: Variables that can influence the decision-making process

Theoretical dimension	Concept	References
Rational factors	Rational factors may be relevant to certain segments and markets.	(Piazza et al., 2018; Ferruz-González et al., 2023; Barquero-Pérez et al., 2020; Kaklauskas et al., 2019)
	Rational factors play a stronger role when the effort required is more significant	(Kaklauskas et al., 2019)
	Artificial Intelligence (AI) technologies can be used to analyse data and extract information	(Beyari et al., 2024)
	Mental processes can be conscious or unconscious	(Cenizo, 2025)
Emotional factors	Decisions are based on feelings and emotional factors	(Ferreira et al., 2024; Polo et al., 2024; Aricò et al., 2018)
	Emotions can come up unconsciously	(Kaklauskas et al., 2020; Landmann, 2023)
	Emotional appeals in communication help to engage consumers and retain attention	(Russo et al., 2023)
	Emotional communication helps to increase trust	(Russo et al., 2023)
	Emotions, values, and ethical preferences	(Lytvyn et al., 2023)
	Sensorial perception experience	(Sadikzade et al., 2024; Cherubino et al., 2017)
	Stories on Instagram vary by gender.	(Fondevila et al., 2020)
	Stories get attention and impact on emotions	(Fondevila et al., 2020)
	Marketing stimuli (emotion, perception, connection, affection)	(Pavličić, 2025)
Avoiding risks	Negative comments generate doubt and frustration	(Ščepková & Zaušková, 2024)
	Positive ones can result in a favourable perception of the purchase and greater engagement	(Ščepková & Zaušková, 2024)
raise awareness	Positive reviews may serve as social proof	(Ščepková & Zaušková, 2024).
	Social advertising and disinterested communication improve the well-being	(Zito et al., 2021)
	Ecological attractive messages	(Ščepková & Zaušková, 2024)
Tools	Social media increasingly emphasizes emotional reactions	(Ščepková & Zaušková, 2024)
	Artificial Intelligence (AI) tools can be used to understand emotions	(Grájeda et al., 2024)
	AI training	(McInnes & Sung, 2025)
	Evaluate attention levels and improve emotional engagement	(Guerrero-Pérez et al., 2025)
	Interface layouts should be used to attract user attention	(Wang et al., 2021)
	Labelling and packaging	(Agudelo et al., 2022)
	High value of music (listen to music)	(Leeuwis et al., 2021)
	Appealing, interactive and immersive visualizations	(Beyari et al., 2024)
	Combining image and sound stimulation	(Polo et al., 2024)
	Humor and emotion (sense of community)	(Micu et al., 2021)
	Visual design of the eco-product	(Ščepková & Zaušková, 2024)
	Innovative design	(Sadikzade et al., 2024)

Source: own elaboration adapted from different authors

Based on these variables, this research presents a proposal to understand consumer behavior. Besides, these factors can be used by eco-friendly and sustainable products campaigns.

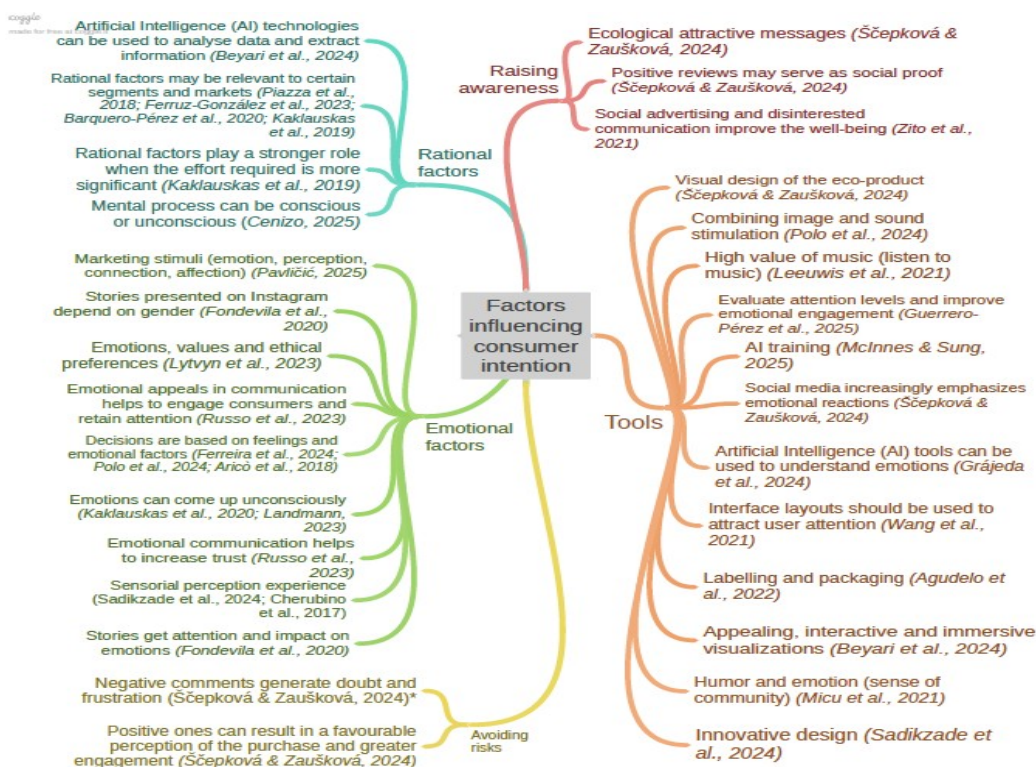
A proposed mind map for understanding sustainable consumer behavior

Countless factors influence the decision to consume (or not) a product. And there are myriad ways to understand this process. However, among all the alternatives, this study assumed that the neuromarketing perspective would be the most effective because it reduces respondents' interpretation bias.

Rational factors may be relevant in certain segments and markets, particularly when the effort is more significant. In addition, technologies such as AI can analyze large amounts of data simultaneously. In this sense, mental processes, whether conscious or unconscious, may be relevant. Most decisions are based on unconscious emotional factors. In this sense, marketing stimuli should use emotional appeals in communication. In addition, stories can impact emotions. It is also suggested that sensory perception, values, and ethical preferences be enhanced. Social media increasingly emphasizes emotional reactions, and communication tools (AI, interface layouts, labeling, and packaging, etc.) expand its reach. In addition, a combination of stimuli, including humor, design, music, and audio, can be used to attract the user's attention. Finally, it should be noted that Instagram stories vary by gender. and negative comments generate doubt and frustration, and positive reviews may serve as social proof.

Considering the different tools and different perceptions, it was also assumed that the depth of understanding could differ. In this sense, a proposed mind map for understanding consumer behavior, specifically applied to eco-friendly and sustainable products campaign, is presented below. Figure 1 shows a mind map of the main factors that can influence consumer behavior.

Figure 1. Mind map proposal: factors of influence sustainable consumer behaviour



Source: own elaboration using coggle.it/diagram/2 on December 2nd, 2025.

² <https://coggle.it/diagram/aS7Is-3oJ3LuUpY5/t/factors-influencing-consumer-intention-on-black-friday>

A strategy to change consumer behavior towards more sustainable choices should understand better the decision process, including rational, emotional and risks involved, as well as their awareness. In addition, the available tools to communicate.

Conclusions

Despite considerations (rational, emotional, and associated risks), can people see the same product differently? To answer this question, the objective of this research was defined: to develop a comprehensive understanding of the factors that influence the consumer decision-making process. On November 27, 2025, this research develops a literature review in Web of Science Core Collection, searching article related to Neuromarketing. The results demonstrated that, in addition to factors originating in neuromarketing, tools can also influence the decision-making process.

Structured the factors into five dimensions: rational factors, emotional factors (widely used in marketing campaigns), factors associated with risk reduction, awareness (in the sense of individual perception of the decision-making process), and the tools that marketing uses and that can also influence the decision. The map mind emerged from the literature review.

The mental process can be conscious or unconscious. And AI technologies can be used to analyze data and extract information. It becomes crucial to understand, for example, which rational factors play a relevant role, particularly when the effort required is more significant, namely for very specific segments and markets.

On the other hand, it is very common to make decisions based on feelings. Emotions can arise, even if unconsciously. When communication explores emotional factors, emotional appeals in communication help to increase consumer engagement and retain their attention. They can even increase trust in messages by identifying with those emotions, values, and affectivity, particularly when associated with ethical preferences. Therefore, experiences should consider sensory perception, and marketing stimuli (emotion, perception, connection, affection) can be reported in the form of stories, as stories attract attention and have an impact on emotions. Considering the relevance of Instagram for stories, it is suggested that the result depends on gender.

In addition, marketing campaigns should be concerned with the impact of the comments. Negative comments generate doubt and frustration, while positive ones can result in a favorable perception of the purchase and greater engagement. As positive reviews can serve as social proof, and publicity and disinterested communication improve well-being, it is suggested that messages be ecologically appealing.

The sympathy, commitment, consistency, and consensus (social proof) associated with the consumer decision-making process can be explained by the desire to belong to a group. However, the factors that influence the decision-making process (Cherubino et al., 2017) are complex. The emotional response to experiences (products or advertisements) (Hou et al., 2016), and facial expressions and expressions associated with emotions can provide a wealth of information (Landmann, 2023) that can aid in assertive communication. It is crucial to understand perception.

There are tools that marketing uses and that can also influence the decision. For example, to promote more environmentally friendly and sustainable purchasing behaviors, considering that social media increasingly emphasizes emotional reactions, AI tools can be used to understand emotions. AI training can help assess attention levels to improve emotional engagement. And interface layouts should be used to attract the user's attention. Other tools

that help increase the assertiveness of communication in the sense of sustainable consumption behaviors are the exploration of labels, packaging, and packages.

The combination of visual stimuli (with attractive, interactive, and immersive visual design of the eco-friendly product) and sound stimuli, with humor and emotion (sense of community) associated with eco-friendly and sustainable consumption, was perhaps the main contribution that emerged from this review. Furthermore, this study argued that the depth (greater or lesser) of awareness of the need for consumption (a process of division associated with greater or lesser need, desire, or expectation) can be a precursor to the decision. People with similar needs may decide on more environmentally friendly and sustainable products, depending on their awareness and consumption preferences. The main limitation is the complexity of the map, which should be applied to each product or message, and measured in future research.

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TRANSPPOSITION OF EUROPEAN APPROACHES IN GEORGIA: THE WASTE MANAGEMENT CODE, EXTENDED PRODUCER RESPONSIBILITY (EPR) AND THE CIRCULAR ECONOMY

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Abstract

The paper examines development dynamics of Georgia's waste management system, focusing particularly on the introduction and implementation of the Extended Producer Responsibility (EPR) instrument within the context of the EU-Georgia Association Agreement. The study reviews the legal and institutional framework for waste management that was established after the Waste Management Code was adopted, and assesses how well it aligns with European Union environmental standards. The paper analyses the main types of waste produced in Georgia, including municipal, hazardous, medical, inert, construction and other specific types of waste, and identifies the key challenges facing the system, such as the lack of infrastructure for separate collection and recycling.

This desk research study includes an analysis of legislative and regulatory acts, strategic policy documents, official statistical data and relevant reports, complemented by expert interviews. Particular attention is paid to assessing the performance of Extended Producer Responsibility organization operating in Georgia, based on data from 2023-2024. The findings suggest that implementing the EPR system has led to a significant rise in the collection and recycling of certain waste streams, particularly tires, oils, batteries and accumulators, and waste electrical and electronic equipment.

The paper also identifies several structural and practical challenges, including delayed enforcement of regulations governing certain waste streams, such as packaging waste and end-of-life vehicles; misalignment of interests between businesses and municipalities; and limited analytical capacity of existing waste management information platforms. The study concludes that EPR is a vital policy tool for improving Georgia's waste management system; however, to enhance its effectiveness, it must be strengthened.

Key words: *Georgia, EU Integration, Waste management, Extended Producer Responsibility, Circular Economy, Recycling Policy, Sustainable Development*

Introduction

Environmental protection is a critical priority when it comes to addressing contemporary global challenges. In recent decades, environmental concerns have increasingly taken centre stage in the political agendas of international institutions and sovereign states alike. The signing of the Association Agreement between the European Union and Georgia was a pivotal moment in Georgia's EU integration, prompting comprehensive reforms across multiple

governance sectors. Beyond the political, economic, judicial and trade dimensions, the Agreement outlines sectoral cooperation aimed at modernizing and aligning domestic policies with EU standards, particularly in the environmental domain. (Tchelidze, 2025)

Waste management remains one of the most pressing environmental issues at global and national levels, requiring the development of robust waste management systems and effective regulatory frameworks. While voluntary initiatives by the private sector play a supportive role, they are insufficient for addressing the problem systematically. In this context, public policy plays a strategic role: establishing an adequate legislative framework provides uniform and mandatory rules for all producers, ensures equitable competitive conditions, and facilitates the transition from a linear economic model to a circular economy. The circular economy emphasizes waste prevention, segregation, reuse and recovery, conceptualizing waste as a valuable economic resource rather than a liability. This approach stimulates innovation and the implementation of advanced technologies and methodologies that enhance material recovery and recycling, thereby contributing to sustainable development and resource efficiency.

Extended Producer Responsibility (EPR) is one of the main policy tools used to achieve sustainable waste management goals. This approach is being increasingly integrated into international practices as a means of allocating environmental accountability to producers. At the same time, the development of comprehensive waste management systems, coupled with enhanced public environmental awareness, has led to growing societal and institutional support for legislation based on EPR principles. By shifting responsibility for waste from public authorities to producers, EPR incentivises sustainable product design and facilitates the transition to a circular economy model, in which waste is seen as a resource rather than a liability.

This paper aims to review the development dynamics of Georgia's waste management system, with a particular focus on the introduction and implementation of the Extended Producer Responsibility (EPR) instrument. The research will assess the effectiveness and role of this mechanism in improving the waste management system and identify the institutional, legal and practical challenges impacting the system's operation and development.

There is limited scientific literature related to the research topic, and most existing publications are primarily descriptive and informational. Only a few studies have been identified within this field, none of which provide an in-depth theoretical or empirical analysis of the issue. Consequently, this study is largely based on legislative and regulatory acts, as well as information available on the official websites of the relevant state institutions. Within the framework of the study, the official website of the waste management system was used alongside reports prepared by various international and local organizations examining the practices, challenges and development prospects of waste management and recycling in Georgia. This approach enables a systematic representation of the current state of the sector.

Research Methodology

This study primarily employs a desk research approach within the framework of qualitative research to provide a comprehensive analysis of the legal, institutional, and policy framework governing waste management in Georgia, with particular emphasis on the transposition of European approaches into national legislation. The selected methodological approach enables a systematic examination of the evolution of Georgia's waste management policy, the implementation of the Waste Management Code, and the introduction of the Extended

Producer Responsibility (EPR) system in the context of the country's approximation to the European Union environmental acquis and the transition towards a circular economy.

The research is based on documentary analysis, involving a systematic review and critical assessment of primary and secondary documentary sources. The primary sources include national legislation, subordinate normative acts, strategic policy documents, action plans, and relevant European Union legal instruments regulating waste management, circular economy, and Extended Producer Responsibility. Particular attention is devoted to examining the extent to which EU legislative principles and policy objectives have been transposed into Georgia's legal and institutional framework.

In addition, the study analyses official reports, policy papers, statistical publications, and implementation assessments produced by Georgian public institutions, international organizations, and other stakeholders operating in the waste management sector. These sources provide the empirical basis for evaluating the progress achieved, identifying existing challenges, and assessing the effectiveness of the institutional and regulatory mechanisms established for the implementation of EPR in Georgia.

The quantitative evidence used in this study consists exclusively of secondary data. No primary empirical data were collected by the authors through surveys, interviews, or other field research methods. Instead, the analysis relies on officially published statistical datasets, monitoring reports, analytical studies, and evaluation documents prepared by national authorities, international and local organizations, as well as Producer Responsibility Organizations (PROs) operating within Georgia's Extended Producer Responsibility framework. The use of multiple independent sources enhances the reliability of the findings through data triangulation and cross-validation.

Furthermore, the analytical framework incorporates elements of comparative legal analysis, enabling a comparison between the European Union's regulatory approach to waste management and the corresponding legislative and institutional developments in Georgia. This approach facilitates an assessment of the degree of legal approximation, the effectiveness of policy transposition, and the consistency of Georgia's regulatory framework with the objectives of the EU Circular Economy Action Plan and broader environmental governance principles.

The combination of documentary analysis, secondary data analysis, and comparative legal analysis provides a comprehensive methodological framework for assessing the implementation of Extended Producer Responsibility in Georgia. It also enables the identification of key legal, institutional, and practical challenges affecting the country's transition towards a circular economy and supports evidence-based conclusions regarding the effectiveness of ongoing policy reforms.

Overview of the Georgian Waste Management System and Waste Streams

The adoption and implementation of practices from European Union member states in Georgia was driven by environmental obligations and the harmonisation of standards mandated under the Association Agreement. In collaboration with the European Union, the Georgian Parliament developed and subsequently approved the Waste Management Code in 2014, which entered into force on January 15, 2015 (Parliament of Georgia, 2015). Prior to this law's enactment, issues related to waste management were only partially regulated through various sectoral legislative acts and, to some extent, by international conventions.

Following the adoption of Georgia's Waste Management Code, work began on developing a modern, national-level waste management system. The Code establishes a five-

tier waste management hierarchy and sets out the requirements and obligations relating to the collection, transportation, recovery and disposal of hazardous, non-hazardous and inert waste. It also regulates planning, registration, permitting and control procedures within the waste management sector (Parliament of Georgia, 2015).

Based on the Waste Management Code, a comprehensive national waste management planning system was initiated. The Code defined the responsibilities of Georgia’s Ministry of Environmental Protection and Agriculture (MEPA) and facilitated the development of a 15-year National Waste Management Strategy and a 5-year National Waste Management Action Plan. Additionally, it established municipal obligations to prepare Municipal Waste Management Plans. Companies generating waste above legally established thresholds were also required to develop Company Waste Management Plans to ensure compliance with national standards and promote accountability in waste handling.

In 2016, based on the Waste Management Code, Georgia adopted its National Waste Management Strategy (2016-2030) and the first Five-Year National Waste Management Action Plan (2016-2020) (Government of Georgia, 2016).

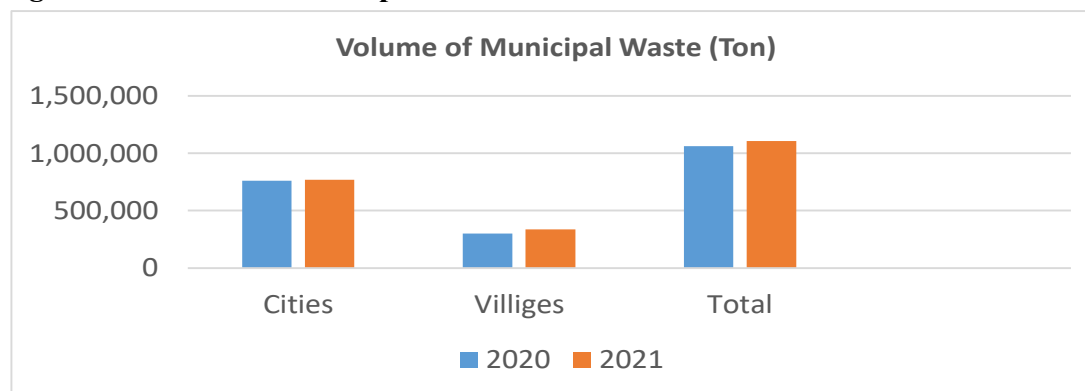
The second National Waste Management Action Plan (2022-2026) introduced additional measures to improve the management of hazardous, plastic, biodegradable, inert, construction and demolition waste, compared to the first Action Plan (MEPA, 2022).

The issue of waste collection and transportation naturally emerged as a significant topic on the country’s political and economic agenda. With regard to municipal waste specifically, comprehensive measures were defined and implemented in phases to align the collection, recycling and disposal systems with international requirements and standards, ensuring the coordination of relevant stakeholders and their active involvement.

It should be noted that data availability for all years is limited to publicly accessible information sources. Accordingly, the study presents an overview of the municipal waste situation based on examples from 2020 and 2021. The volume of municipal waste generated in urban and rural settlements in these years was estimated using the waste generation index, which is derived from data on waste disposed of at landfills and population size.

According to an analysis of the available data, the total volume of municipal waste generated in Georgia in 2020 was 1 061 007 tons, with 760,942 tons originating in urban areas and 300,065 tons in rural areas. This figure increased to 1 104 952 tons in 2021, with 768,257 tons generated in cities and 336,695 tons in rural areas (MEPA, 2023).

Figure 1. Volume of Municipal Waste

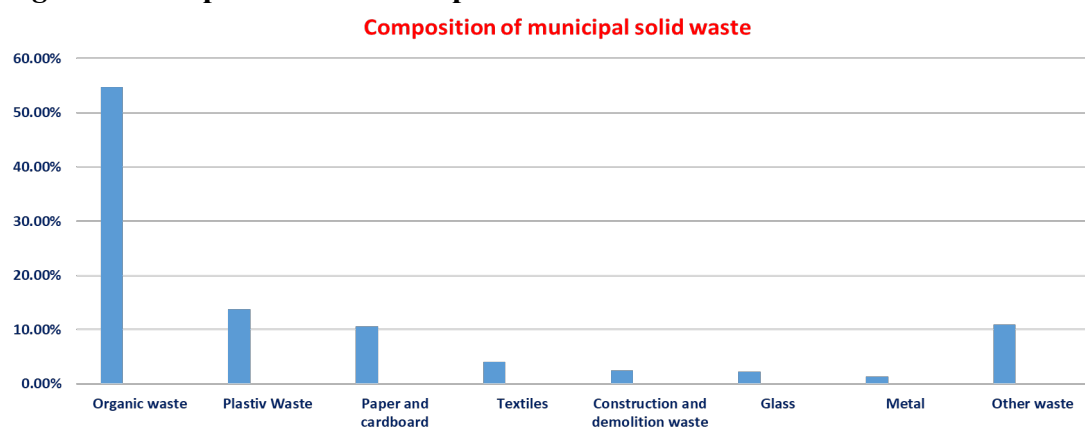


Source: *Mcarmoebliis gapartoebuli valdebulebis organizaciebis mier migceuli sedegebis angarisi. 2023 wlis angarisi [2023 Report on the Results Achieved by Extended Producer Responsibility Organizations]*

Analysis of waste composition, conducted to determine the typical structure of waste streams generated and the proportion of various components, indicates that municipal waste in Georgia consists of:

- Organic waste - 54.7%
- Plastic waste - 13.8%
- Paper and cardboard - 10.6%
- Textiles - 4.1%
- Construction and demolition waste - 2.5%
- Glass -2.3%
- Metal - 1.4%
- Other waste -11% (MEPA, 2023)

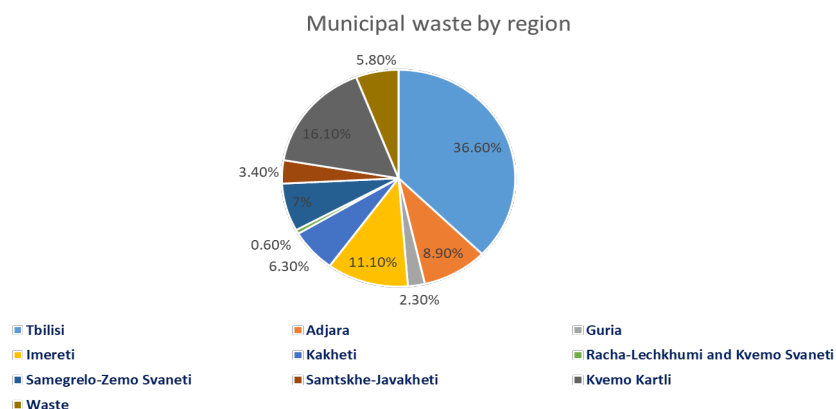
Figure 2: Composition of Municipal Solid Waste



Source: *Mcarmoebli gapartoebuli valdebulebis organizaciebis mier migceuli sedegebis angarisi. 2023 wlis angarisi [2023 Report on the Results Achieved by Extended Producer Responsibility Organizations]*

Regarding municipal waste in 2020 and 2021, the situation is as follows:

Figure 3: Municipal Waste by Region



Source: *Mcarmoebli gapartoebuli valdebulebis organizaciebis mier migceuli sedegebis angarisi. 2023 wlis angarisi [2023 Report on the Results Achieved by Extended Producer Responsibility Organizations]*

Notably, alongside regional data, separate statistics are provided for the capital city, Tbilisi, which highlight the significant challenges associated with municipal waste management within the city. Various studies have projected municipal waste generation and collection for settlements up to 2030 based on Georgia’s population, tourism development forecasts, and expected volumes of specific waste types. These studies estimate an annual increase of 0.6% to 1.2%, underscoring the urgency of addressing this issue in the country (MEPA, 2023).

Currently, Georgia faces challenges in the separate collection of hazardous municipal waste, which is often disposed of alongside non-hazardous waste in landfills, posing risks to the environment and public health. Healthcare institutions are responsible for the management of medical waste and enter into contracts with medical waste management operators. The Ministry of Internally Displaced Persons from the Occupied Territories, Labour, Health and Social Affairs, in collaboration with the Ministry of Environmental Protection and Agriculture of Georgia, provides regulatory oversight. Despite implemented measures, some medical waste still reaches landfills without prior treatment.

Over 2 million tons of inert, construction and demolition waste are generated annually in Georgia. The small scale of the inert waste recycling industry and limited business interest often result in the uncontrolled disposal of construction and demolition waste. Some of this waste is used for municipal back filling activities. Therefore, establishing an effective system for collecting and processing inert, construction and demolition waste remains a critical challenge for the country.

Key challenges in the field of waste collection and transportation include:

- ensuring nationwide coverage of municipal waste collection services;
- Modernizing waste collection and transportation equipment.
- Implementing separate waste collection
- Development of public-private partnership policies.

It is precisely in this context that the significant responsibility introduced by the Extended Producer Responsibility (EPR) system becomes apparent. Under this system, product manufacturers and/or importers are held accountable for the collection and treatment of specific hazardous waste, thereby safeguarding human health and the environment.

Extended Producer Responsibility - Practice in Georgia

Sweden's pioneering role in the Extended Producer Responsibility (EPR) policy has facilitated its gradual expansion across various industrial sectors, setting an example for the effective implementation of environmental strategies. This model has transcended European borders and become increasingly relevant in Georgia. Georgia's National Waste Management Strategy (2016-2030) identifies specific waste streams for EPR, detailing the annual volumes of waste generated in the country, including batteries and accumulators, electrical and electronic waste, waste oils, tires, packaging materials and end-of-life vehicles (Government of Georgia, 2016). Notably, the strategy emphasizes that a significant challenge is the absence of separate collection schemes for municipal waste, leading to most of this waste ending up in landfills.

The Waste Management Code mandates the implementation of the Extended Producer Responsibility (EPR) system at the national level. To facilitate the execution of the legislation and the operationalization of the system, various analytical and practical supporting documents were developed, alongside the implementation of awareness-raising campaigns regarding EPR.

In 2017, the Ministry of Environmental Protection and Agriculture of Georgia initiated the project "Support for the Implementation of the Extended Producer Responsibility

Principle in Accordance with the Waste Management Code." The project was implemented by Georgia's Environmental Outlook (GEO) with the support of the United Nations Development Program (UNDP) and the Government of Sweden (Sida). European expertise was also integrated into the project through the expert assistance of the German organization adelphi and the local consulting company PMO. The *Manual on Extended Producer Responsibility* published within the framework of the project provided a detailed explanation of EPR goals and objectives, approaches, products subject to EPR, financing schemes, system efficiency, and mechanisms for ensuring enforcement by state authorities and EPR organizations (GEO, 2019).

As national officials noted, "The support from the European Union, the United Nations Development Program (UNDP), and the Swedish International Development Cooperation Agency (Sida) is profoundly significant in the process of implementing the Extended Producer Responsibility reform. It is through these reforms that we adopt the best European practices, which will greatly benefit the waste management sector in the future" (Entrepreneur Georgia, n.d.).

The "Manual on Extended Producer Responsibility" proved to be a turning point for Georgia's waste management sector. While EPR had previously remained a theoretical obligation, this manual provided it with a practical framework. Although the "Extended Producer Responsibility - Producer's Guide" was subsequently published in 2021, it was the original EPR Manual that established the intellectual foundation for the technical regulations developed and adopted between 2018 and 2020. It detailed how European directives could be adapted to the Georgian reality. In effect, it served as the first road-map for the private sector, laying the groundwork for institutional dialogue among three key parties: the state (regulator), business (financier), and the municipality (operator). It clearly delineated rights and responsibilities to prevent the duplication of functions. Consequently, the abstract articles of the "Waste Management Code" were transformed into a tangible action plan. Concurrently, meetings were held with central and local government authorities, international and donor organizations, the private sector, chambers of commerce, business associations, and other stakeholders to familiarize them with the requirements of Georgian legislation regarding EPR and best international practices. (GEO, 2019)

To ensure the implementation of Extended Producer Responsibility, the Government of Georgia approved four technical regulations on May 25, 2020:

1. "On the Management of Waste Batteries and Accumulators" (Government Resolution No. 324)
2. "On the Management of Waste Tires" (Government Resolution No. 325)
3. "On the Management of Waste Electrical and Electronic Equipment" (Government Resolution No. 326)
4. "On the Management of Waste Oils" (Government Resolution No. 327). (Waste Management system)

The regulations came into force on September 1, 2020. However, the recycling and recovery targets are mandatory from 2023. (MEPA, 2020).

Legislation governing waste subject to extended producer responsibility provides for the management of two additional waste streams: packaging and end-of-life vehicles. All the streams have been considered when defining the goals to be achieved by Georgia. (Hainrich Boll Stiftung, 2020)

Table 1: Recyclable Waste to be achieved by Georgia

Recyclable waste	By 2020	By 2025	By 2030
Batteries	20%	50%	80%
Oils	50%	75%	90%
Packaging materials	40%	75%	90%
Electrical devices	20%	50%	80%
Tires	50%	70%	90%
Accumulators	60%	80%	90%
End-of-life vehicles	20%	50%	80%

Source: Waste management in Georgia, Heinrich Böll Stiftung, 2020

The remaining two regulations, which concern end-of-life vehicles and the largest volume of packaging waste, have been awaiting approval for several years. The regulation requiring the private sector to manage packaging waste was drafted several years ago with the participation of EU experts. According to the latest data, this regulation was expected to come into force in the first quarter of 2024. However, the timing of the other regulations remains uncertain. (Mcarmoebliis gafarToebuli valdebuleba - ra aperxebssesaputi masalebis narcenebis migebas, 2025)

In July 2024, the rules for calculating the target indicators for waste collection, reuse, recovery, and recycling within the framework of Extended Producer Responsibility were approved.

In accordance with the technical regulations, producers (including importers) are balanced to ensure the separate collection of waste generated from the specific products they place on the Georgian market (tires, oils, batteries and accumulators, electrical and electronic equipment) and its treatment in compliance with environmental requirements according to the annual target indicators defined by the technical regulations. Producers fulfill this obligation either individually or collectively, through Extended Producer Responsibility (EPR) organizations.

Naturally, in the process of studying this issue, institutional mechanisms were of great interest on one hand; however, to create a comprehensive picture, it became necessary to analyze specific achievements.

Research

During the research, the electronic waste management system was examined, as well as institutional mechanisms. This platform provides comprehensive information on various issues, including Extended Producer Responsibility (EPR). Consequently, the activities of EPR-registered organisations were analysed based on their performance results in 2023 and 2024.

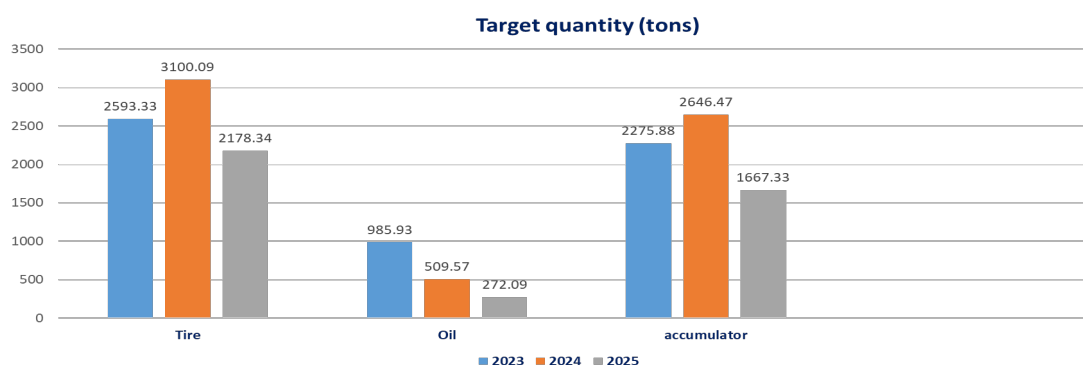
Operating under the Ministry of Environmental Protection and Agriculture of Georgia, the waste management platform contains all relevant legislation and registration procedures related to waste management. Unfortunately, collection points are not displayed separately, nor is detailed information provided on their locations. However, the platform presents specific information regarding EPR organisations authorised by the Ministry, including:

1. Tegeta Green Planet: collective compliance scheme for waste oils, waste tires and waste accumulators.
2. The Waste Management Business Association - operates a collective compliance scheme for waste oils, waste tires and waste accumulators.
3. Georgian Producers Extended Liability Association - operates a collective compliance scheme for waste oils, waste tires, waste accumulators, and waste electrical and electronic equipment.
4. Amboli 2: individual compliance scheme for waste accumulators.

Alongside organisational information, the platform provides details of contact persons and contact information, as well as compliance schemes. However, it lacks specific information on the operational activities of these organisations. This complicates the systematic collection and analysis of information on EPR organisations, and highlights the need to improve the waste management system platform further. Nevertheless, it is important to note that these EPR organisations have highly developed, comprehensive websites that provide clear, detailed information on their activities.

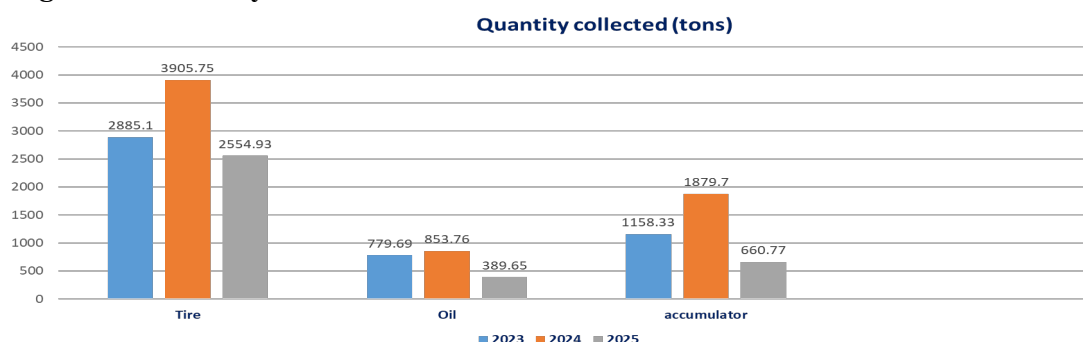
The “Tegeta Green Planet” runs a trilingual website in Georgian, Russian and English - <https://tgp.ge/en>. According to data from 2022-2025, the organisation has enrolled around 350 producers from the tire, oil, and battery sectors. Tegeta Green Planet has clearly defined plans and initiatives intended for implementation over a multi-year period. These include attracting private investment in waste management infrastructure, identifying and collaborating with licensed recycling plants and transport operators, establishing and equipping collection points, and creating new employment opportunities. An analysis of the organization’s activities over the years reveals the following trends: (Tegeta Green Planet)

Figure 4: Target Quantity



Source: <https://tgp.ge/en>

Figure 5: Quantity Collected



Source: <https://tgp.ge/en>

Although the organisation has not yet fully achieved the annual collection targets set out in its operational plans, its current progress is encouraging. Tegeta Green Planet is making consistent efforts to align its activities with institutional obligations and international standards. It has published the Eco-Tips Book, (Presentation of the book “Eco-Tips” took place in 11 schools in Tbilisi, 2025) which provides comprehensive information on environmental topics and eco-friendly practices. The book explains the concept of Extended Producer Responsibility (EPR) and details the management of automotive waste. It also highlights the importance of environmentally responsible behaviours. The organisation has also developed informational posters and shared them on social media.

Tegeta Green Planet actively seeks partners to promote pollution prevention and reduction, sustainable resource use, and mitigation of global warming, and provides the necessary application forms for collaboration. Preliminary recycling contributions have been outlined by product category for 2025, offering interested stakeholders comprehensive guidance.

Similarly, the NGO Waste Management Business Association (WMBA) maintains a bilingual (Georgian and English) website - <https://wmba.com.ge/> however, only the Georgian version was accessible during the research period. The WMBA platform effectively consolidates all relevant legislative acts, facilitating stakeholder engagement and operational transparency. The organisation maintains a broad network of partners and is actively pursuing future collaborations with waste transport operators. It explicitly demonstrates its readiness to cooperate with authorised physical and legal entities for the collection and transportation of waste oils, tires and batteries. Consequently, registration within the official electronic waste management system is a primary requirement for engagement in waste management activities.

The activities of the “Georgian Producers Extended Liability Association” are thoroughly documented on the Wasteless website - <https://wasteless.ge/home/ka/> which is available in both Georgian and English. The organisation works with 13 contractors who are responsible for managing conventional and LED lamps, crushed glass, industrial oils, plastics, mercury-containing lamps, tires, rubber products and accumulators. Information on the locations of external electronic waste collection boxes, including those installed in cinemas, is publicly accessible. (Wasteless)

Since March 2025, the organisation has expanded its public awareness efforts through a new eco-friendly podcast format, continuing to educate the Georgian population on waste management issues. The podcast can be subscribed to on a dedicated YouTube channel (Ecomegobruli podkasti) which hosts 16 thematic videos. Although subscriber numbers are currently modest, the videos have relatively high viewership, indicating significant audience engagement. Furthermore, the organisation has introduced a system of incentive prizes linked to its activities, with the aim of increasing public interest and participation in its initiatives.

Finally, the activities of the non-profit organisation Amboli 2 are highlighted on its Facebook page, as well as on widely recognised Georgian platforms such as Marketer.ge and Entrepreneur Georgia. Amboli 2 received its authorisation from EPR in 2023 and has since been operating actively, demonstrating positive dynamics and efforts to expand its activities within Georgia and internationally, particularly in the collection and recycling of accumulators.

Overall, analysis of the waste management system indicates that the official platform plays a significant role in consolidating legislative and administrative information. However, it provides limited insight into the practical activities of EPR organisations, which makes the

systematic collection and analysis of operational data difficult. It can be observed that all authorised EPR organisations are actively engaged in waste collection and recycling, placing considerable emphasis on partnerships, public awareness campaigns and alignment with international standards. At the same time, these organisations differ in terms of the scale of their operations and their modes of communication. Nevertheless, the dynamic growth observed suggests a positive trajectory that is likely to enhance waste collection and recycling in line with established target indicators in the future.

During this research, particular attention was given to analyzing the reports concerning the outcomes achieved by Extended Producer Responsibility (EPR) organizations, based on the reports for 2023 and 2024.

It is noteworthy that EPR organizations are required to submit a detailed report on the completed activities to the Ministry of Environmental Protection and Agriculture of Georgia by April 30 of the year following the reporting period. These reports are subsequently published on the Ministry’s official website by May 31 of each year.

As of 2023, the EPR electronic registry lists over 11 200 registered producers and importers. Among them, 7 948 are involved in electrical and electronic equipment, 1027 in tires, 1227 in batteries and accumulators, and 1000 in oils.

The obligation to meet target collection volumes was introduced in 2023. Accordingly, the following amounts of waste were collected by Extended Producer Responsibility (EPR) organization during 2023: Waste tyres: 5 873 tons; Waste oils: 2 301 tons; Waste batteries and accumulators: 2 340 tons; Waste electrical and electronic equipment: 614 tons (Mcar-moeblis gapartoebuli valdebulebis organizaciebis mier migceuli sedegebis angarisi, 2023 wlis angarisi, 2024)

According to the 2024 report, the EPR electronic registry recorded 15 288 producers and importers. Compared to 2023, the number of registered producers/importers has increased across all waste streams - Electrical and electronic equipment: 10 988; Tires: 1 303; Batteries and accumulators: 1 724; Oils: 1 273. (Mcar-moeblis gapartoebuli valdebulebis organizaciebis mier migceuli sedegebis angarisi, 2024 wlis angarisi, 2025)

Table 2: Key EPR Indicators in Georgia (2023-2024)

2023		Total	2024		Total
Electrical and electronic equipment	7 948	11 200	Electrical and electronic equipment	10 988	15 288
Tires	1027		Tires	1 303	
Batteries and accumulators	1227		Batteries and accumulators	1 724	
oils	1000		oils	1 273	

Source: Mcarmoeblis gapartoebuli valdebulebis organizaciebis mier migceuli sedegebis angarisi. 2024 wlis angarisi [2024 Report on the Results Achieved by Extended Producer Responsibility Organizations]

The primary focus is on the four organisations under study and their registered producer-importer members, with respect to specific waste streams such as oils, tires and batteries/accumulators. The collection and recycling performance of each organisation is analysed separately. Overall, the number of collection and recycling points increased across Georgia as a whole. Concurrently, the total quantities of specific waste collected and recycled

by the four organisations in 2024, by waste stream, are as follows: (Mcarmoebulis gapartoebuli valdebulebis organizaciebis mier migceuli sedegebis angarisi. 2024 wlis angarisi, 2025)

Table 3: Collection and Recycling Results of EPR Organizations (2024)

2024	Waste type	Collected (ton)	Recycled (ton)
	Waste tires	10 031	8 451
	Waste oils	3 146	2 777
	Waste batteries and accumulators:	2 977	2 947
	Waste electrical and electronic equipment	1 540	1 446

Source: Mcarmoeblis gapartoebuli valdebulebis organizaciebis mier migceuli sedegebis angarisi. 2024 wlis angarisi [2024 Report on the Results Achieved by Extended Producer Responsibility Organizations]

A comparison of the indicators clearly shows that progress has been made in terms of the quantity of waste collected in 2023. Unfortunately, the 2023 report did not provide any statistical data on recycled waste. However, although the 2024 figures are not yet fully released in terms of recycling, they indicate a positive trend. It should also be noted that both the collection and recycling volumes are expected to increase by 2030, which highlights the significant responsibility of EPR organizations in this regard.

Among the various waste streams, waste tires are the most significant. Currently, the recycling sector for tires is underdeveloped, and it is not possible to recycle large quantities efficiently. Nevertheless, there is potential to produce rubber and other materials from this waste, which highlights the need for new investments and the establishment of additional recycling facilities. Legislative provisions also allow for the export of waste tires, which could be a future option. However, there is currently greater emphasis on using them as an energy source in production processes. For example, experts cite a cement plant in Georgia that is installing new furnaces to utilize the energy generated by incinerating waste tires.

The situation with packaging materials and end-of-life vehicles is different. Packaging materials play a significant role in everyday life, serving to protect and store products, and to promote them. They are expected to be lightweight yet durable, and can be made from plastic, metal, glass, paper, wood, or a combination of different materials. Once the contents have been used, the packaging becomes waste that must be disposed of properly.

To address the environmental issues associated with packaging waste, European countries began implementing specific measures as early as the 1990s. These measures included the introduction of extended producer responsibility (EPR), waste management hierarchies and other economic instruments, as well as the relatively recent circular economy approach. This has positioned EU countries as leaders in the recycling sector. Legislation is increasingly setting higher and more ambitious targets for the recovery of valuable materials and the efficient use of resources. The recycling rate for packaging waste initially stood at 25%, was later increased to 55%, and reached 65% by 2018.

According to statistics, approximately 195 000 tons of packaging waste were generated in Georgia in 2017, the vast majority of which ended up in the environment or landfills. The volume of packaging waste increases annually. Georgia can leverage Europe's long-standing experience to establish recycling schemes through private and public initiatives. Currently, recycling is at a specific stage of development; however, the existence of end-user

infrastructure indicates potential for further sector growth. Municipalities must implement separate collection systems, which require waste containers, garbage trucks, and sorting facilities. Clearly, one of the primary prerequisites for success is the active participation and engagement of the public in waste separation. (Mcarmonoblis gapartoebuli valdebuleba saqartvelosi, 2019)

In this regard, it must be noted that the recycling of packaging materials is hindered by disputes over technical regulations. Business entities have criticized changes made to the original version of the regulations - which were initially developed by municipalities in collaboration with EU experts - attributing these modifications to the municipalities' limited understanding of the core of the issue. While municipalities perceive this matter merely as a mechanism for sanitary cleaning, it involves the interests of both the business sector and society. The issue is addressed under the "Polluter Pays" principle, which consistently places businesses in a position of investment rather than profit-making, thereby highlighting the responsibility of waste generators as well.

The situation regarding end-of-life vehicles is equally challenging. The annual number of end-of-life vehicles is approximately 12,000, the vast majority of which are abandoned on the streets of Georgia. This situation is unacceptable, as ELVs are classified as hazardous waste and, without proper treatment, can lead to environmental degradation. With the implementation of the Extended Producer Responsibility principle, the final owner will have the opportunity to utilize a network of collection points covering the entire territory of Georgia. Delivering the end-of-life vehicle to an authorized collector free of charge will become a prerequisite for deregistering the vehicle. This approach will encourage the neutralization and dismantling of waste, as well as the reuse/recycling of approximately 80% of metals and other valuable materials contained within the vehicle.

Conclusions

The research revealed that establishing and developing a waste management system in Georgia is closely linked to the obligations arising from the Association Agreement with the European Union, as well as the process of aligning environmental policies with European standards. Adopting the 'Waste Management Code' and developing relevant strategic and regulatory documents created a legal and institutional framework for establishing a modern waste management system. However, the research findings indicate that the practical implementation of this framework is still associated with significant challenges.

The study demonstrated that introducing the Extended Producer Responsibility (EPR) system in Georgia is one of the most important policies for improving the management of specific and hazardous waste. Analysis of data from 2023–2024 confirms that EPR organisation activities have increased waste collection and recycling rates, particularly for tires, oils, batteries and electrical and electronic equipment. Concurrently, positive trends are evident in infrastructure expansion, partnership network strengthening, and public awareness enhancement.

Despite the progress achieved, the research highlights systemic and structural challenges that hinder the waste management system from operating at full capacity. These include insufficient development of the separate collection of municipal waste and limited capacity in the recycling industry for certain waste streams, particularly tires and construction waste. There has also been delayed implementation of regulatory technical standards for packaging waste and end-of-life vehicles. Another challenge is the lack of clear coordination and delineation of responsibilities between state institutions, municipalities and the private sector.

In conclusion, further development of the waste management system in Georgia and enhancement of the EPR mechanism's effectiveness require a comprehensive, consistent policy approach. This entails strengthening institutional capacities, promoting investment in recycling infrastructure, refining legislative regulations and implementing them in a timely manner, and ensuring active public engagement in waste separation and environmentally friendly practices. Meeting these preconditions will lay the foundation for a circular economy-based waste management system in Georgia, achieving long-term environmental, social and economic benefits.

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CORPORATE SUSTAINABILITY DUE DILIGENCE DIRECTIVE (CSDDD) IN PRACTICE: ANALYSIS OF OBLIGATIONS AND IMPLEMENTATION CHALLENGES

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Abstract

Nowadays, the importance of recognizing negative impacts on the environment is experiencing significant increase. There is a growing tendency for companies to harmonise their business activities with the principles of corporate sustainability, thus encouraging the development of a circular economy. In this regard, the EU is adopting the Corporate Sustainability Due Diligence Directive (CSDDD), thereby establishing a harmonised legal framework at EU level.

The paper analyses the provisions of the CSDDD through the principle of due diligence that companies should implement in their business operations, and the possible impacts of its implementation in practice. Given the shortcomings of the Directive's provisions in terms of monitoring the performance of companies, the EU responds to the excessive administrative burden foreseen by the CSDDD by adopting the Omnibus I package, which significantly narrows the circle of liable companies and dilutes its original purpose.

The paper provides a doctrinal and critical legal analysis, examining the importance of due diligence in corporate governance. It also concerns Directive's simplification package, Omnibus I, as the EU's response to the increased administrative burden on companies that was foreseen by the CSDDD. Following the analysis, the limitations arising from the Omnibus I package are examined, with an emphasis on raising the thresholds for companies and the lack of strict regulation on civil liability. Based on these changes, the paper assesses the consequences for effective corporate governance and provides practical guidelines for their quality implementation in practice.

Key words: CSDDD, circular economy, due diligence, corporate sustainability

Introduction

Until recently, in matters of corporate sustainability, companies were mostly only required to report on their impacts on human rights and the environment, and such procedures were voluntary and varied from country to country (Sinnig, and Zetzsche 2025). Consequently, a Directive came into force that introduces an obligation to effectively prevent negative impacts in global supply chains, introducing a harmonised legal framework for all EU Member States. (Sinnig, and Zetzsche, 2025) Thus, the EU Directive on Corporate Sustainability Due Diligence (CSDDD) was adopted on 24 May 2024, and it refers to the obligations of

companies to enforce due diligence procedures in their business (Giovannone, 2024). These consist of identifying, mitigating and minimizing environmental and human rights losses in the operations of companies, all with the aim of aligning their business operations with the transition to a circular economy (Bueno et al, 2024).

Although the importance of sustainable practices has become more widely recognized, many companies still do not have effective management systems, as well as measures to prevent or mitigate the harmful social and environmental consequences of their business activities (Bueno et al, 2024). Therefore, the CSDDD imposes obligations on companies and their value chains regarding due diligence and the environment, in order to encourage responsible business, including the transition to a circular economy.

The paper, through doctrinal and critical legal analysis, elaborates on the provisions of the CSDDD Directive and the possibility of their implementation. The paper specifically addresses the simplification package of the Directive - Omnibus I, in response to requests in terms of reducing the administrative burden for companies. Accordingly, the differences compared to the original version of the CSDDD and the resulting shortcomings arising from them are analysed. Based on these changes, the paper assesses the consequences for corporate governance and provides guidelines for their quality implementation in practice.

The material scope

The primary function of the Directive is to introduce due diligence requirements for companies, all with the aim of ensuring sustainable business operations. According to the Directive, companies are required to identify and, ultimately, prevent all potential negative impacts on the environment and human rights that may arise from companies' daily operations, the operations of their subsidiaries, and also the operations within their value chains (Jäger et al, 2023). In this sense, it was necessary to establish a harmonised EU regulatory framework that contributes to a sustainable, and responsible strategy to global value chains (Art. 31, CSDDD).

The legal rules established in the Directive are strictly applicable to companies that meet certain conditions, such as the company's turnover, and a threshold for the number of employees. Accordingly, the Directive applies to the following companies: 1) EU companies with an average of more than 1000 employees and a worldwide net turnover exceeding EUR 450 000 000 in the last financial year (Art. 28, CSDDD); 2) companies from third countries (non-EU members) which have achieved a net turnover of at least EUR 450 000 000 (Art. 29, CSDDD); 3) companies that do not individually meet the specified thresholds but qualify as the “ultimate parent company” of a group that does (Art. 29, CSDDD). It is significant to mention that only companies that fulfil the defined thresholds for two consecutive financial years fall within the scope of the Directive (Art. 27, CSDDD).

Based on the Directive, companies covered by the Directive must incorporate due diligence into their operations and management to forestall and mitigate harmful effects on human rights and the environment in their operations, those of their subsidiaries and partners (Art. 38, CSDDD). They must also monitor performance, engage with stakeholders, have a grievance mechanism and report publicly on their activities (Art. 38, CSDDD). Besides, the purpose of the CSDDD is to promote respect for human rights, environmental protection, but also to prevent potential abuse of the system by companies (Jurić et al, 2022). What is more, the concept of due diligence aims to reduce negative impacts on the environment, such as land degradation, biodiversity loss, pollution and many others (Art. 32, CSDDD).

When it comes to due diligence and its importance, the Directive states that companies should incorporate it into their risk management policies and mechanisms, including a code of conduct and procedures covering the company, subsidiaries and their business partners (Art. 39, CSDDD). The policy is based on a risk assessment and applies to all employees, including temporary and non-standard employees, and in key functions such as procurement and recruitment (Art. 39, CSDDD). Therefore, the main issue regulated by the Directive is precisely the need to strengthen sustainability in corporate governance systems.

In response to this question, the unwillingness of Member and strong pressure from major economic actors resulted in the adoption of the "Stop-the-Clock" Directive was adopted in April 2025, as a tool to remove political pressure, which officially postponed the application of the due diligence rules (Alemanno, 2025). At the same time, at the initiative of the European Commission, and in line with the new guidelines for strengthening competitiveness, a systematic model of “simplification” of the law was introduced through the Omnibus package, which significantly reduces the scope of the due diligence analysis obligations prescribed by the CSDDD, which will be discussed in more detail in the second part of the paper (Alemanno, 2025).

Due diligence obligations

Starting from the fact that the CSDDD contains an obligation to implement due diligence and climate change mitigation, the question arises as to what role the application of due diligence plays in the implementation of such procedures (Velluti, 2024). These are manifested in human rights violations and abuses, for example, non-payment of the minimum wage, forced labor, use of children for labor, or discrimination against employees, which threatens the dignity of employees, employee rights, and reduces the social responsibility of companies (Ciacchi, 2024). When it comes to the environment and the circular economy, the negative (human) impact is clearly manifested in various processes of environmental destruction, such as harmful emissions, wastewater discharges into rivers, air pollution, improper waste disposal, deforestation and numerous ways of damaging ecosystems, which threaten biodiversity, human health and climate stability (Pacces, 2023).

Since due diligence procedures must cover the companies’ business activities and the activities of subsidiaries and all related entities in the value chain, this includes both entities with which there is a direct contractual relationship (direct partners), as well as those that operate without such a contract but perform activities or provide services related to the business (indirect partners) (Pacces, 2023). Moreover, it is important to define the concept of the chain of activities, which includes all the processes that precede the actual production or provision of services, such as the procurement and supply of raw materials, their storage, and the development or design of products and services (Art. (3)(1)(g)(i), CSDDD). Value chains describe the way companies and activities are linked in global production and trade (Gereffi et al, 2005). Given the requirements of the CSDDD for companies to monitor and manage risks throughout the entire supply chain, due diligence becomes an important mechanism that provides for risk assessment and control of compliance with human rights and environmental standards within the supply chain.

Member States, in accordance with the CSDDD, ensure that companies carry out due diligence in the domain of and environmental protection and human rights, based on risk assessment and undertake the activities, as follows:

“(a) integrating due diligence into their policies and risk management systems in accordance with Article 7;

(b) identifying and assessing actual or potential adverse impacts in accordance with Article 8 and, where necessary, prioritising actual and potential adverse impacts in accordance with Article 9;

(c) preventing and mitigating potential adverse impacts, and bringing actual adverse impacts to an end and minimizing their extent in accordance with Articles 10 and 11;

(d) providing remediation for actual adverse impacts in accordance with Article 12;

(e) carrying out meaningful engagement with stakeholders in accordance with Article 13;

(f) establishing and maintaining a notification mechanism and a complaints procedure in accordance with Article 14;

(g) monitoring the effectiveness of their due diligence policy and measures in accordance with Article 15;

(h) publicly communicating on due diligence in accordance with Article 16.” (Art. 5(a)-(h), CSDDD). The mechanisms described above will be analysed in detail in the remainder of this paper.

When it comes to incorporating due diligence into corporate practices and risk management mechanisms, such policies should be developed in collaboration with employees and designed to include a description of how a particular company approaches the implementation of due diligence. This includes a code of conduct that its subsidiaries and business partners should follow, in order to effectively implement due diligence; and a description of the procedures in place to implement, monitor and verify compliance with due diligence obligations and the established code of conduct (Art. 7(1)(2) (a)-(c)(3), CSDDD).

Moving on to the matter of identifying and assessing actual or potential adverse impacts, Member States shall ensure that appropriate resources, such as independent reports, are used (Art. 8(3), CSDDD).

Related to preventing and mitigating potential adverse impacts, in order to fulfil this obligation, companies must take several key steps. They must develop and implement a preventive action plan with clearly defined deadlines for their implementation, seek contractual guarantees from direct business partners to ensure compliance with the company’s code of conduct, make the necessary financial or non-financial investments in various processes, make the necessary changes to their own business plan and similarly provide support to small and medium-sized enterprises (SMEs) in their chain of activities, as well as cooperate with other entities (Art. 10(2)(a)-(f), CSDDD). However, if potential negative effects cannot be prevented by applying appropriate measures, the company is obliged to apply a measure of last resort, which is manifested in refraining from establishing new or extending existing relationships with the business partner in whose chain of activities it originated (Art. 10(6), CSDDD). In this regard, Morris’s critical approach to contractual assurances questions whether contractual assurances are an appropriate measure of due diligence, given that the CSDDD states that contractual assurances alone will not be sufficient to meet the duty of due diligence (Morris, 2025). This is because the implementation of prescribed obligations requires real monitoring and verification of the effectiveness of their implementation, and the approach provided by the Directive enables formal compliance with the law without preventing negative impacts on the environment (Morris, 2025).

Furthermore, ensuring the remediation of actual adverse impacts provides for the obligation to remove the damage by the enterprise itself in cases where the enterprise caused the actual adverse impact (Art. 12(1), CSDDD). In other words, the company cannot shift this obligation to others.

Next, carrying out meaningful engagement with stakeholders means that companies should, when consulting with their stakeholders, provide relevant information so that

consultations can be conducted in an effective and transparent manner (Art. 13(1)(2), CSDDD). That implies that the focus is on joint collaboration throughout the due diligence process.

Moreover, when establishing and maintaining a notification mechanism and a complaints procedure, it is important to provide for a publicly accessible and fair, transparent procedure for resolving them, especially in cases where the complaint is considered unfounded. In this context, the importance of confidentiality of the identity of the person or organisation submitting the complaint, in accordance with national law, is stressed in order to prevent any form of retaliation, i.e. in order to avoid endangering the safety of the complainant (Art. 14(3), CSDDD).

Moving on to the matter of monitoring the effectiveness of their due diligence policy and measures, it is important to highlight that Member States ensure that regular assessments are carried out of their own operations, as well as those of their subsidiaries and business partners linked to the company's supply chains (Art. 15, CSDDD). The aim is to monitor the implementation of the measures and assess their effectiveness in identifying, reducing and eliminating negative impacts in order to minimise their level.

Finally, a public due diligence statement brings up that Member States shall ensure that undertakings inform themselves about the issues covered by the Directive by publishing an annual report on their websites (Art. 16, CSDDD). All the above-mentioned and analysed obligations further strengthen the responsibility of companies and enable better control of the implementation of the Directive itself. The aim of these policies is to enable companies to effectively manage their operations within value chains. In this way, the reduction of negative impacts on human rights and the environment is achieved. Conversely, Sinnig, and Zetzsche warn that the different implementation mechanisms of the CSDDD may lead to inconsistent application in practice and examine the Directive's actual ability to effectively prevent violations of environmental standards in global value chains (Sinnig, and Zetzsche, 2025).

It is evident that the Directive sets demanding obligations for the purpose of identifying the impact of business on human rights and the environment. With this in mind, it provides mechanisms for assessing and eliminating risks throughout the value chain and points to the necessity of transparent reporting on the measures taken. However, the broad scope of the Directive makes it difficult to apply the rules in complex global value chains, creating heavy administrative and financial burdens. Therefore, in the next part of the paper, the original text of the Directive and its application in practice will be critically examined. Through the package of simplification of obligations established by the Directive, Omnibus I, which increases the feasibility of applying the Directive, the question of the real impact of such measures on the corporate governance of companies is raised.

Implementation

In some EU countries, there are already legal frameworks that require large companies to monitor and assess (negative) impacts on human rights and the environment (Starc-Meclejan, 2025). For instance, France adopted the Law on the Duty of Vigilance (Loi de vigilance) in 2017, and Germany adopted the Supply Chain Due Diligence Act (Lieferkettengesetz) in 2021 (Starc-Meclejan, 2025). Such different approach of the countries had an impact on shaping corporate responsibility in Europe, by creating a harmonised legal framework - the CSDDD. When it comes to sustainable economy, the process of implementing CSDDD involves taking certain steps that aim to help companies successfully master its implementation in business practice. Such a process, as mentioned earlier, includes

stakeholder engagement, promoting transparency and responsible business practices (Omerovic, 2024). Therefore, companies are obliged to provide their stakeholders with accurate and complete information in a clear and transparent manner, following all the procedures described so far in this paper, which ensures the monitoring and supervision of stakeholders and policies related to various business entities (Witte, 2025).

Besides, the CSDDD sets mandatory standards for companies operating in the EU or those connected to the EU market. It is important to understand how companies react to the Directive as these reactions also affect other market and non-market actors. Repeatedly, some EU companies already implement due diligence procedures, and Germany and France already have laws defining standards for human rights and environmental protection (Jäger et al, 2023). Those companies, that already implement due diligence, can benefit in the following ways: better control over the value chain, reduced risk, strengthened governance and increased competitiveness, according to Jäger et al, 2023. Since companies in some countries have already faced legal consequences due to similar regulations, the economic impact of the CSDDD on them will be smaller than on companies in parts of the EU where such laws have not yet existed (Jäger et al, 2023).

In addition, the Directive provides for changes in supply chains so that companies can stop working with suppliers that violate human rights and replace them with those that operate in accordance with the rules set out in the Directive (Jäger et al, 2023). This approach encourages responsible behaviour along the entire value chain and reduces the negative externalities associated with unethical practices (Jäger et al, 2023). Also, the result that companies may face when implementing the Directive is the closure of those business activities that cannot comply with the required standards (Jäger et al, 2023). This outcome usually affects only the least competitive companies, i.e. those companies that would otherwise have difficulty maintaining their operations under conditions of fair market competition (Jäger et al, 2023).

Furthermore, the implementation of the Directive also brings with it some obstacles for companies when it comes to its application in practice. Therefore, the next part of the paper analyses the key challenges arising. The business community generally supports sustainability objectives but also points out that excessive and costly reporting requirements at EU level may to some extent undermine the competitiveness of EU companies in the global market (BusinessEurope, 2021).

Firstly, the implementation of the Directive is a financial burden on SMEs and seriously threatens their liquidity (Dempere et al, 2024). Unlike large corporations, smaller companies have fewer resources and lower margins, so any new cost affects them much more strongly. Also, the entire process of companies complying with the obligations prescribed by the Directive, from documentation to ongoing monitoring, requires large initial investments in the development of new systems that would enable what the Directive requires (Dempere et al, 2024). Therefore, from a financial perspective, the adoption of the Directive may affect the financial situation of individual companies in a way that increases their financial costs. In addition, the directive also provides for fines for non-compliance with its provisions, in order to ensure that the directive is applied in practice. Fines are based on the company's worldwide net turnover, and the maximum fine may be up to 5% of the company's worldwide net turnover in the financial year preceding the imposition of the fine (Art. 27(4), CSDDD). Since maximum fines reach at least 5% of net global turnover, it is clear that these are not symbolic amounts, but a serious financial blow that can threaten the stability of even the strongest companies. Given the challenges mentioned, the financial risk of the Directive is visible from two perspectives. On the one hand, the costs of compliance itself represent a huge burden on

the liquidity of SMEs that do not have capital reserves. On the other hand, large corporations face the threat of fines, which makes any oversight failure extremely costly. So, whether it is the cost of compliance or the risk of sanctions, the Directive brings a financial pressure that no entrepreneur can ignore (Dempere et al, 2024).

Secondly, according to the report by Stichting Onderzoek Multinationale Ondernemingen (SOMO), the Directive also contains rules that, when applied, may undermine its effectiveness (de Leth, 2024). For example, it obliges companies to conduct due diligence only on their direct suppliers (Tier1), while most suppliers from high-risk countries remain outside the scope of supervision (de Leth, 2024). This means that the biggest problems with human rights and environmental violations cannot be effectively prevented in practice. Tier1 suppliers of large EU supermarkets mainly come from safe countries, while products such as bananas come from risky regions, such as Southeast Asia, with high risk of serious human rights violations (de Leth, 2024). Therefore, according to SOMO, taken from the VSME Standard (Voluntary Sustainability Reporting Standard), developed by the European Financial Reporting Advisory Group (EFRAG), the term "VSME shield" is explained, which means that SMEs are not covered by full reporting obligations and that their administration is facilitated. For this reason, the introduction of measures protecting SMEs suppliers from the obligation to provide data for due diligence further blocks the flow of information, as SMEs companies may refuse to share data, which prevents supermarkets from carrying out real due diligence (de Leth, 2024).

Thirdly, shifting costs to smaller suppliers, especially in poorer countries, poses another financial problem for smaller companies (Mieszkowska, 2024). Smaller companies may not be able to pay for the checks, reports and adjustments that large buyers require, which can push them out of supply chains and prevent them from doing business with EU companies (Mieszkowska, 2024). Accordingly, they are potentially limited in their ability to successfully implement the CSDDD.

Next, according to Mieszkowska (2024), Eu companies may withdraw from countries where there is a higher risk of human rights violations or poor working conditions in supply chains for fear of penalties, which could consequently result in job losses and worsening working conditions in those countries (as cited in Commission Staff Working Document, 2022). Such a sudden departure can lead to job losses, contract terminations and the "relocation" of production to even less regulated countries, as noted by Mieszkowska (2024).

Although the normative part of the CSDDD provides solutions regarding the obligations of due diligence of sustainable business, the highlighted negative effects do have a significant impact on the future application of the Directive and the harmonisation of laws in the Member States. What the CSDDD lacks are mechanisms for effectively ensuring the monitoring of their implementation and they often remain only on paper, without actual implementation in practice. In order for real implementation to occur, it is necessary to fully provide the tools to verify all the aforementioned obligations foreseen in the CSDDD. According to Mieszkowska, although the CSDDD has significantly contributed to the environmental regulatory framework by introducing due diligence obligations, its implementation may have unpredictable negative consequences, including the termination of business relationships with suppliers in high-risk regions and the shifting of compliance costs to smaller suppliers, which may undermine human rights and environmental protection objectives.

Although the process of harmonizing the Directive into national legislation began in accordance with the plan envisaged by the Directive, it was abruptly interrupted in February 2025 with the introduction of the Omnibus I package. This legislative move by the European Commission, taken during the adjustment period, marked a shift towards deregulation under

the pretext of preserving competitiveness (Jäger et al, 2025). The key instrument of this shift, the "Stop the Clock" Directive, did not only bring about a technical postponement of the deadlines, but also opened the way for due diligence changes to the content of the CSDDD itself, which is analysed in the remainder of the paper.

Impact of the Omnibus I Package on the Scope of Obligations

Although 2025 was supposed to be marked by the harmonisation of the CSDDD Directive, a regulatory turnaround occurred at the EU level, resulting in the final adoption of the Omnibus I package in December 2025 (Jäger et al, 2025). This process, initiated by the European Commission's announcement in February 2025, represented a systematic response to the issue of declining EU competitiveness and geopolitical instability (Alemanno, 2025). It was adopted with the aim of reducing the administrative burden by at least 25% for all companies and simplifying reporting obligations (Baumüller, 2025). Furthermore, it included a number of proposals aimed at amending and postponing key sustainability rules, primarily within the CSRD and CSDDD directives (European Commission, 2025). Accordingly, Alemanno (2025) warns arguing that it is a deliberate circumvention of democratic rules. According to his analysis, Omnibus I directly violates fundamental principles of EU law for two reasons: lack of evidence and exclusion of the public (Alemanno, 2025). In fact, the public was not included in the discussion when it came to the adoption of the Omnibus I package, and changes at the EU level are introduced without evidence and expert analysis that would confirm their justification (Alemanno, 2025).

Namely, the simplification of the Directive included, first of all, the adoption of the "Stop the Clock" directive from April 2025, which officially postponed the application of the reporting rules (CSRD) by two years and the deadline for the application of the CSDDD by one year (Jäger et al, 2025). This delay was not only of a technical nature. It was used as a way to reduce the pressure on decision-makers, by giving the opportunity to interest groups and opponents of stricter rules to weaken the main parts of the Directive (Alemanno, 2025). That move resulted in a reduction in the number of areas covered by harmonization and the deletion of key provisions on responsibility. Moreover, contrary to the objective of the CSDDD, whose intention was for companies to conduct due diligence within the entire value chain, the adoption of the Omnibus I package significantly narrows the due diligence obligations, narrowing the scope of application to only Tier1 suppliers (Jäger et al, 2025). Therefore, the introduction of such a mechanism also resulted in slowing down the application of sustainable standards that the Directive originally envisaged (Jäger et al, 2025).

Furthermore, this package also includes narrowing the scope of civil liability for damage caused in supply chains (Jäger et al, 2025). Namely, the original text of the Directive provided for the possibility of sanctioning damage caused as a result of human rights violations. However, the new rules adopted by the Omnibus I package shift the focus from the legal protection of victims to administrative supervision, which represents the impossibility of achieving real change.

Moreover, the thresholds for the application of the rules were further raised to 5,000 employees and 1.500.000.000 EUR in turnover, which ultimately results in a reduction of the companies covered by as much as 70% compared to the original text (Jäger et al, 2025). By raising the threshold to extremely large companies, it once again confirms that the Omnibus I package is based on the mere fulfilment of formal obligations, without room for achieving real efficiency and the objectives of the CSDDD.

The key role in justifying these changes was played by Mario Draghi’s report on the future of EU competitiveness (Draghi, 2024). In his work, Draghi directly identified the CSDDD as a significant administrative obstacle that stifles EU industry (Draghi, 2024). It was his approach, which indicates the priority of competitiveness over environmental and social objectives, that opened the way for the EU Council to raise the thresholds for the application of the Directive, with the aim of transforming the strict rules into a much more lenient regulatory framework.

The paper points out that this approach circumvents EU constitutional principles (Article 11 TEU and Article 296 TFEU) because such important changes for human rights and sustainability are implemented too quickly, without public participation and without clear evidence of a real impact on competitiveness (Alemanno, 2025). Aránguez Díaz (2026) emphasizes how this process of deregulation of corporate sustainability was carried out in a short time without public consultation or impact assessment. Although the introduction of Omnibus I is officially presented as a necessary step towards reducing administrative burden on companies, the established rules indicate that it aims to systematically weaken the rules adopted by the CSDDD (Alemanno, 2025).

From the analysis of the Omnibus I package, it is evident that the purpose of the objectives of the CSDDD is being reduced to a simplified obligation to report, with the adopted changes that occurred with the aim of simpler implementation of due diligence obligations. By enacting the analysed restrictions, corporate governance remains focused on short-term profits, and concern for human rights is reduced to formal reporting without any real change in practice.

The implications of this approach also need to be seen in the context of consumer rights. Many consumers across Europe want to buy products with a concern for the social and environmental conditions of the products, but they do not have reliable information about how the products are made (Jäger et al, 2025). In doing so, they are left to rely on voluntary labels and certificates, which they often cannot trust (Jäger et al, 2025). In addition, relying on unverifiable certificates also affects fairness in the market; companies that invest in sustainability may be unfairly penalized because they have higher costs compared to their competitors. Ultimately, due diligence obligations represent an important step towards more responsible business and greater transparency, but they do not in themselves solve all the problems of market inequality and do not give consumers new direct rights. Their real value depends on how they are implemented in practice.

Conclusions

The aim of this analysis was to examine the content of the CSDDD, as well as the potential unintended consequences for global supply chains and environmental protection. It is also important to point out that in addition to guidelines for achieving sustainable business, the Directive also introduces restrictions, such as financial sanctions and other limitations, which may affect the effectiveness of the implementation of due diligence measures.

It is evident that the CSDDD represents a significant step forward when it comes to regulating corporate responsibility and sustainability within global value chains. By creating a harmonised legal framework for all companies on the EU market, the CSDDD seeks to contribute to greater legal certainty. The regulation introduced by the CSDDD also requires companies to systematically manage sustainability risks, which in the long term can increase the reputation of companies with investors and consumers. The adoption of the CSDDD has significantly contributed to environmental protection, primarily because its provisions oblige

companies to recognize and assess the negative impacts of their business operations on the environment. Accordingly, more responsible resource management and the promotion of a circular economy are encouraged.

However, despite the effort to establish a harmonised regulatory framework for sustainable business operations, the adoption of the Omnibus I package significantly changed the direction of the Directive itself. Instead of strict control throughout the supply chain, the focus has shifted to reducing administrative costs and protecting the competitiveness of EU companies. The introduction of measures such as raising the thresholds for companies, denying the right to compensation and other restrictions of the Omnibus I package means that in practice only a small number of companies will be monitored, while violations in the supply chain will be harder to detect. This has shifted the risk back to consumers who still lack reliable information about products, raising the question of whether implementing these rules of thumb will be able to change corporate behaviour or will it just remain a form-filling exercise.

Although Omnibus I simplifies the process for companies to the detriment of consumers and human rights, such a relaxation of standards is unsustainable in the long term. Smart corporate governance must go beyond the minimum requirements set by current law but should build systems that are ready for the inevitable tightening of rules that will eventually have to correct current shortcomings.

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GENDER DIFFERENCES IN CONSUMER MOTIVATIONS FOR SUSTAINABLE CONSUMPTION IN ENVIRONMENTALLY SUSTAINABLE RESTAURANTS

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Abstract

Modern tourism increasingly emphasizes sustainable and environmentally responsible consumption practices. Within the tourism industry, restaurants play an important role in promoting sustainability through the adoption of environmentally responsible business models, including resource efficiency, waste reduction, and the use of locally sourced products. In this context, environmentally sustainable restaurants represent an important mechanism for encouraging sustainable consumption and supporting the principles of the circular economy. The aim of this study was to examine tourists' motivations for consuming in environmentally sustainable restaurants and to identify potential gender differences in these motivations.

The research was conducted in the Republic of Serbia, with a particular focus on Vrnjačka Banja, the country's leading spa tourism destination, during the period from August to October 2025. Data were collected through a structured questionnaire using a seven-point Likert scale. Descriptive statistics and the non-parametric Mann–Whitney U test were employed to analyze the data and examine gender-based differences.

The findings indicate a generally high level of motivation among respondents to choose environmentally sustainable restaurants, particularly due to opportunities to experience local culture and discover new food tastes. Statistically significant gender differences were identified, with female respondents demonstrating stronger preferences for environmentally sustainable restaurant options. The results suggest that sustainable consumption practices are becoming increasingly relevant in gastronomic tourism and highlight the role of environmentally sustainable restaurants in supporting circular economy objectives. The study contributes to a better understanding of consumer behavior in sustainable hospitality and provides insights that may support the development of fairer and more sustainable consumption practices within tourism destinations.

Key words: *sustainable consumption practices, circular economy, environmentally sustainable restaurants, consumer motivation, gender differences, gastronomic tourism*

Introduction

The growing interest of consumers in sustainable and environmentally responsible tourism and hospitality offerings has stimulated significant transformations within the industry. These changes are reflected in the adaptation of business models to the principles of environmental protection, social responsibility, and circular economy practices. In this context, consumption choices increasingly represent not only individual preferences but also mechanisms through which consumers support sustainable and fair production and consumption systems. Restaurants that implement environmentally sustainable practices provide an important setting for examining how consumers respond to sustainability-oriented offerings and how these choices contribute to broader circular economy objectives.

Previous research indicates that women tend to make more socially and environmentally responsible consumption decisions, which may be associated with higher levels of empathy and concern for others and the wider community (Hawkins, 2012). Numerous empirical studies have shown that women generally demonstrate stronger pro-environmental attitudes and greater concern for environmental issues than men (Ramstetter & Habersack, 2020). Due to their higher environmental awareness, women are often more willing to engage in circular and sustainable consumption practices (Vinkóczy et al., 2024; Lorincová & Osvaldová, 2025) and to pay premium prices for products and services that generate positive environmental outcomes (Lee, 2011). Furthermore, women are more likely to purchase organic products and prefer locally sourced food compared to men (Bellows et al., 2010; Olivas & Cañete, 2012).

Within the hospitality sector, environmentally sustainable restaurants represent a practical example of how circular economy principles can be translated into consumer experiences. By promoting local sourcing, resource efficiency, waste reduction, and responsible business practices, such restaurants contribute to sustainable tourism development while simultaneously encouraging more responsible consumption behavior. Understanding the motivations that drive consumers to choose these restaurants is therefore important not only from a marketing perspective but also from the standpoint of sustainable and fair consumption.

In accordance with the growing importance of sustainability and circular economy principles in tourism and hospitality, this paper aims to contribute to a deeper understanding of gender differences in motivations for consuming in environmentally sustainable restaurants. The study focuses on the extent to which male and female consumers differ in their motivations, attitudes, and future behavioral intentions related to sustainable consumption within gastronomic tourism.

The objectives of this research are threefold: (a) to examine the importance of gastronomic experiences during travel among male and female tourists; (b) to compare gender differences in motivations for choosing environmentally sustainable restaurants; and (c) to analyze the extent to which these motivations influence respondents' intentions to choose destinations that offer environmentally sustainable restaurant options in the future.

The findings are expected to provide valuable insights for restaurant managers, destination marketers, and policy-makers seeking to promote sustainable and fair consumption practices. A better understanding of gender-based differences in consumer motivations may support more effective market segmentation and the development of hospitality offerings aligned with sustainability objectives, thereby contributing to the advancement of responsible tourism and circular economy principles.

Literature review

Tourism and Sustainable Consumption in the Context of Green Travel

Environmental challenges have become unavoidable, necessitating immediate action by modern society to foster green development, safeguard biodiversity, and address the demands of the green transition and decarbonization (Fritsche et al., 2020; Torun & Aslan, 2023). As one of the fastest-growing sectors, the tourism industry has the potential to become a significant contributor to global greenhouse gas (GHG) emissions (Filimonau et al., 2013; Lenzen et al., 2018; Obersteiner et al., 2021), particularly through hospitality-related activities (Singh et al., 2014; Filimonau et al., 2021). The tourism sector is also among the largest consumers of water resources worldwide. Studies conducted in hotels across different regions indicate that tourists consume, on average, approximately 350 liters of water per day, often exceeding 300 liters per person (Garzia et al., 2023).

As a result, green tourism has attracted growing attention from researchers, policy-makers, and industry stakeholders due to its potential to reduce the environmental impacts of tourism activities. Existing studies emphasize strategies aimed at encouraging more sustainable visitor behavior (Hou & Wu, 2021; Nelson et al., 2021) and optimizing tourism demand in line with sustainability objectives (Sun et al., 2020). These approaches are closely aligned with the principles of responsible consumption and the circular economy, which seek to minimize resource use and environmental degradation while maintaining tourism competitiveness.

Within this context, green tourism has emerged as an important framework for mitigating the negative environmental consequences of tourism development. Literature generally approaches the concept from two perspectives. The first defines green tourism as tourism activities taking place in natural environments, with a strong focus on conserving natural resources (Andari & Setiyorini, 2016). The second perspective considers green tourism as an inherently environmentally responsible form of tourism. Similarly, Furqan et al. (2010) distinguish two main purposes of the term “green tourism”: presenting destinations as attractive and environmentally preserved places for recreation and emphasizing that tourism activities should be conducted without causing environmental harm.

The literature further suggests that green travel is closely linked to sustainable transportation choices that reduce energy consumption and greenhouse gas emissions while promoting public health. Such alternatives include public transportation, carpooling, walking, and cycling (Jia et al., 2017). These practices not only contribute to environmental protection but also support broader sustainable consumption goals within tourism systems.

In the context of climate change and increasing environmental degradation, green travel and tourism represent important pathways toward more sustainable production and consumption patterns. Nevertheless, the adoption of such practices among tourists remains relatively slow, partly due to a limited understanding of their broader environmental and societal significance (Kasim, 2016; Gabor et al., 2023). While previous studies have primarily focused on environmental attitudes and sustainable tourism behavior, less attention has been paid to how consumers' motivations influence sustainable consumption choices within hospitality settings. Therefore, this study addresses this gap by examining tourists' motivations to consume in environmentally sustainable restaurants and by exploring whether gender differences shape these consumption preferences.

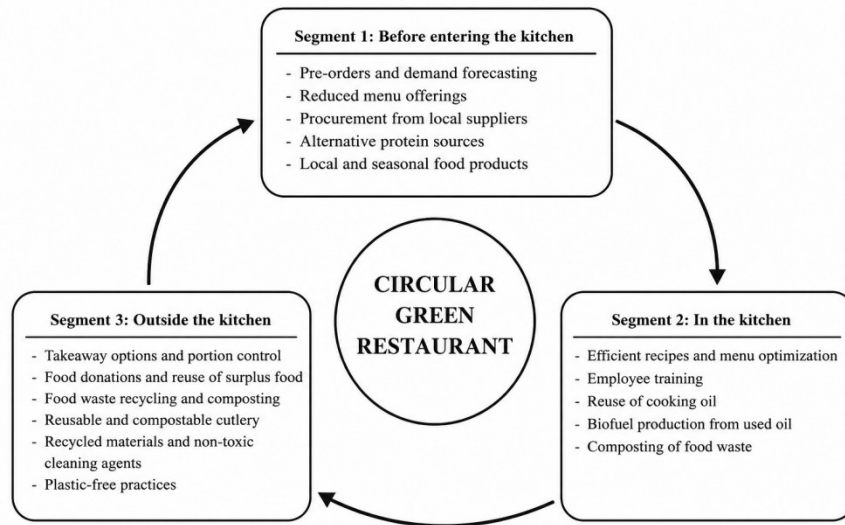
Environmentally Sustainable Restaurants as Drivers of Sustainable Consumption Practices

Restaurants represent an important component of the tourism industry and play a significant role in shaping tourist experiences. In contemporary tourism, restaurants are no longer viewed solely as places where basic physiological needs are satisfied; they also reflect the social, cultural, and environmental values of a society. As a result, consumption experiences in restaurants encompass both tangible and intangible dimensions of value creation (Suhartanto et al., 2025). Increasingly, consumers are paying attention to environmental and social aspects of restaurant operations, including food waste reduction, energy efficiency, and responsible resource management. Research suggests that restaurants adopting such ecological values exert a stronger influence on consumer attitudes and preferences (Kim & Eves, 2012). Consequently, environmentally sustainable restaurants have emerged as an important element of sustainable hospitality and responsible consumption.

The literature indicates that sustainable practices are becoming increasingly important in the restaurant sector, similarly to developments observed in the hotel industry. Due to the intensive use of resources, particularly water, energy, and disposable products, there is growing pressure to improve environmental performance and reduce ecological impacts (Perramon et al., 2014; Shin & Cho, 2023). Previous studies have shown that the implementation of sustainable practices strengthens restaurant image and brand reputation, while simultaneously contributing to financial performance and the sustainable development of local communities.

In response to these trends, the concept of environmentally sustainable restaurants has gained considerable attention in academic and professional literature. Such restaurants implement a variety of environmentally responsible practices, including recycling, composting, efficient water and energy use, and waste reduction initiatives. They also increasingly prioritize locally sourced, seasonal, and organic food products within their offerings (Julião et al., 2018). Particular emphasis is placed on the principles of the three “Rs” (reduce, reuse, and recycle) and the two “Es” (energy and efficiency), reflecting a comprehensive approach to sustainable business management.

Within the circular economy framework, environmentally sustainable restaurants can be viewed as a response to the growing demand for responsible production and consumption practices. Through their consumption choices, consumers increasingly seek transparency regarding food quality and origin, sustainable production processes, respect for consumer rights, and adherence to principles of fair consumption. At the same time, they demonstrate a willingness to support, including financially, hospitality businesses that contribute to environmental protection and local community development (Madanaguli et al., 2022; Biloslavo & Janković, 2025).

Figure 1: Circular model for green restaurant

Source: Adapted from Biloslavo & Janković (2025)

In the literature, environmentally sustainable restaurants are often referred to as “green” or “eco-friendly” restaurants that operate according to environmentally responsible principles (Green Restaurant Association, 2025). Organizations and professional networks promoting sustainable restaurant concepts advocate a broad range of practices that support environmental protection, economic viability, and social sustainability (Maynard et al., 2020; Della Corte et al., 2025). These practices include responsible waste management, reduced water and energy consumption, the use of local, seasonal, and organic ingredients, and the incorporation of Fair Trade products whenever possible. In addition, sustainable restaurants seek to ensure fair working conditions, adequate employee compensation, and active engagement with local communities through socially beneficial initiatives (The Sustainable Restaurant Association, 2025).

The Green Restaurant Association (GRA), founded in the United States in 1990, has played a pioneering role in promoting environmentally responsible restaurant practices. Through the development of scientifically grounded certification standards, the organization established a systematic framework for evaluating sustainability performance in restaurant operations. According to GRA guidelines (2016), restaurants seeking green certification must satisfy criteria related to water conservation, waste management, sustainable building materials, responsible sourcing of food, renewable energy use, recyclable materials, and pollution reduction. In this way, the GRA represents an institutional model that integrates environmental, economic, and social dimensions of sustainability within hospitality operations (Lorenzini, 1994).

Maynard et al. (2021) further emphasize that restaurants can only be classified as sustainable when their activities are aligned with multiple dimensions of sustainability. Consequently, sustainability assessment tools play a critical role in identifying existing practices and determining the improvements necessary to achieve sustainability standards and certification requirements.

Modern consumers demonstrate a higher level of environmental awareness than in previous decades (Kwok et al., 2016), although knowledge regarding environmentally sustainable restaurants remains relatively limited (Schubert et al., 2010). Understanding the

motivations that influence consumers' decisions to support sustainable restaurant practices is therefore essential for promoting responsible consumption and advancing circular economy objectives within tourism. Despite the growing relevance of sustainable hospitality, research on environmentally sustainable restaurants remains limited in Serbia, particularly regarding gender-related differences in consumer motivations and sustainable consumption behaviour. By addressing this gap, the present study contributes to the literature on sustainable consumption practices, consumer behaviour, and circular economy implementation in hospitality, while providing insights relevant to small open economies such as the Republic of Serbia.

Methodology

Study area. The empirical research was carried out in the Republic of Serbia, specifically in Vrnjačka Banja, the country's most prominent spa destination. Data were gathered between August and October 2025, a period characterized by increased tourist flows and a heterogeneous visitor structure in terms of socio-demographic and travel-related characteristics. This setting enabled the inclusion of respondents with diverse backgrounds and travel experiences. Although the study was conducted in a single destination, its relevance extends beyond the local context. Since the research examines tourists' attitudes toward environmentally sustainable restaurant practices, the findings may offer insights applicable to other destinations that have already adopted, or intend to adopt, similar sustainability-oriented restaurant concepts. Therefore, the results contribute to a broader understanding of sustainable hospitality management and destination development within the framework of circular economy principles.

Sample and Data Collection. The study population consisted of tourists visiting Vrnjačka Banja during the survey period. A purposive sampling strategy was applied in order to include respondents of different genders, age groups, and educational backgrounds, thereby ensuring a variety of perspectives regarding sustainable restaurant consumption. The questionnaire was distributed in printed form at several tourism-related locations, including restaurants, hotels, cafés, and tourist information centers. After data screening, a total of 102 completed questionnaires were retained for statistical analysis.

Research instrument. Data collection was conducted using a structured questionnaire developed on the basis of previous studies in the fields of sustainable tourism and gastronomy (Gheorghe et al., 2021; Hernández-Rojas et al., 2022; Elsehely & Elsayed, 2024). The instrument was designed to assess the motivational factors associated with tourists' decisions to visit restaurants implementing environmentally sustainable practices. The questionnaire comprised two sections. The first section collected socio-demographic information, including gender, age, educational attainment, and travel frequency. The second section focused on motivational statements related to experiences and perceptions of environmentally sustainable restaurants. Responses were measured using a seven-point Likert scale ranging from 1 (“strongly disagree”) to 7 (“strongly agree”).

Data Analysis. The collected data were processed using both descriptive and inferential statistical techniques. Descriptive statistics, including mean values, standard deviations, and minimum and maximum scores, were calculated to provide an overview of respondents' attitudes and motivations. To examine gender-related differences in motivational factors, the non-parametric Mann–Whitney U test was employed. In addition, box-plot visualizations were used to facilitate the interpretation of group differences. Statistical analyses were performed using IBM SPSS Statistics software (version 17).

Results and Discussions

The socio-demographic profile of the respondents is presented in Table 1. Among the 102 surveyed tourists, women accounted for 62.75% of the sample, while men represented 37.25%. A similar gender distribution has been reported in previous tourism surveys, where female respondents were found to be more willing to participate in questionnaire-based research (Ćurčić et al., 2009).

Regarding age structure, the largest proportion of respondents belonged to the 18–25 age group (51.9%), followed by respondents aged 26–35 years (19.2%). In terms of educational attainment, more than half of the participants held a university degree (51.9%), while 21.2% had completed master's studies and 9.6% held a PhD degree.

To obtain an initial overview of respondents' attitudes, descriptive statistical analysis was conducted. The results indicate that all motivational statements achieved mean values above the midpoint of the scale ($M > 4.00$), suggesting generally positive attitudes toward environmentally sustainable restaurant practices and a relatively high level of agreement with the proposed statements.

Table 1: Descriptive Statistics of Motivational Statements

code	Mean	Std. Deviation
Mt1	5,2745	1,61157
Mt2	5,3431	1,48587
Mt3	5,451	1,51969
Mt4	5,1667	1,62336
Mt5	5,2451	1,53788
Mt6	5,2843	1,51152
Mt7	5,5784	1,36749
Mt8	5,1765	1,50518
Mt9	5,6373	1,40571

Source: Author

Table 1 presents the descriptive statistics of the motivational statements. All mean values exceed the midpoint of the scale ($M > 5.00$), indicating generally positive attitudes toward environmentally sustainable restaurants.

The highest mean scores were recorded for MT9 ($M = 5.64$), related to menu diversity, and MT7 ($M = 5.58$), referring to fresh and locally sourced ingredients. The lowest, although still positive, values were observed for MT4 ($M = 5.17$) and MT8 ($M = 5.18$). Standard deviations ranged from 1.37 to 1.62, indicating moderate variability in responses.

To further examine whether these attitudes differ by gender, inferential statistical analysis was conducted. The first step was to assess the importance of gastronomic experiences during travel among male and female respondents (Table 2).

Table 2: Gender differences in the importance of gastronomic experiences during travel

Gender	Mean	SD
Male	5,026315789	1,6189226
Female	5,625	1,201850425

Source: Authors' calculations.

As presented in Table 2, women assigned greater importance to gastronomic experiences during travel ($M = 5.63$; $SD = 1.20$) than men ($M = 5.03$; $SD = 1.62$). While respondents of both genders generally evaluated gastronomy as an important component of the travel experience, female tourists expressed stronger agreement with this view. In contrast, male respondents exhibited a wider dispersion of responses, suggesting a broader range of perceptions regarding the contribution of gastronomy to overall travel satisfaction. These observations are in line with previous studies indicating that travel motivations and experiential preferences may vary according to gender (Kim & Eves, 2012; Björk & Kauppinen-Räsänen, 2016).

Figure 2: Travel Motivated by Local Cuisine According to Gender

Male | 55.3% Yes | 44.7% No |
 Female | 37.5% Yes | 62.5% No |

Source: Author

Note: The difference was statistically significant ($p < 0.05$).

Figure 2 shows that male respondents were more likely to report traveling primarily to experience local cuisine (55.26%) than female respondents (37.50%). Conversely, a larger proportion of women indicated that local food was not a primary travel motive (62.50%). These findings suggest that culinary motivations may be more pronounced among male tourists in the studied sample.

Table 3: Gender Differences in Motivations for Choosing Environmentally Sustainable Restaurants

Code	Statement	Male Mean Rank	Female Mean Rank	Z	p	Effect size (r)
MT1	Green restaurants help me better understand local culture	45.53	55.05	-1.610	0.003*	0.16
MT2	Green restaurants introduce me to new tastes of local food	44.66	55.56	-1.852	0.004*	0.18
MT4	I recommend the experience to others	47.95	53.61	-0.956	0.339	—
MT5	Visiting destinations with green restaurants is an authentic experience	46.87	54.25	-1.249	0.212	—
MT9	Green restaurants should offer diverse menus	49.00	52.98	-0.682	0.495	—

Source: Author

Note: The difference was statistically significant ($p < 0.05$).

Table 4 presents the results of the Mann–Whitney U test examining gender differences in selected motivational factors associated with environmentally sustainable restaurants. Female respondents obtained higher mean ranks across all analyzed statements, indicating a generally stronger agreement with sustainability-related attributes.

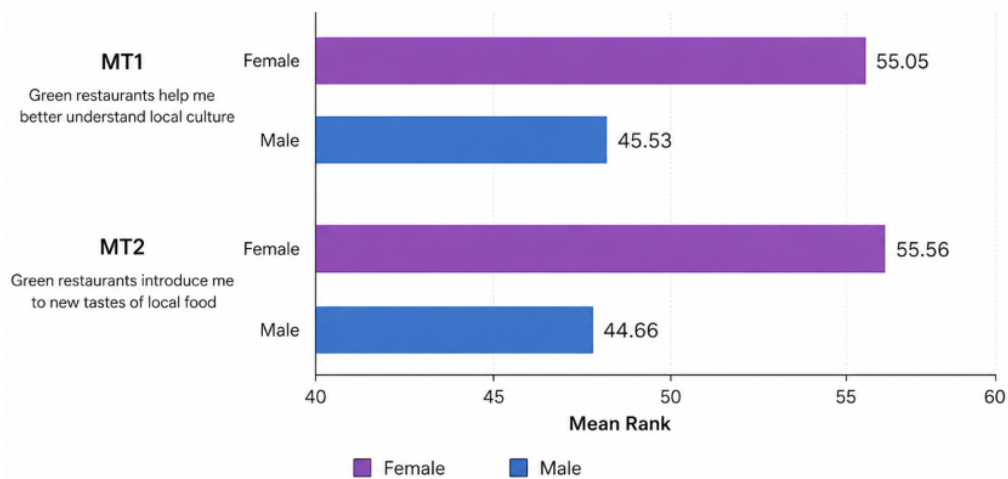
Statistically significant gender differences were identified for MT1 and MT2. Women assigned greater importance to the role of environmentally sustainable restaurants in

facilitating cultural learning (MT1: $Z = -1.610$, $p = 0.003$) and in providing opportunities to discover new local food tastes (MT2: $Z = -1.852$, $p = 0.004$). Although significant, the corresponding effect sizes were small ($r = 0.16$ and $r = 0.18$), suggesting modest practical differences between male and female respondents.

For the remaining motivational dimensions, no statistically significant gender differences were observed ($p > 0.05$). These findings indicate that men and women share relatively similar views regarding recommendation intentions, perceptions of authenticity, and the importance of menu diversity in environmentally sustainable restaurants.

In order to additionally show the differences in motivations between the sexes, diagrams were created for the claims where statistically significant differences were recorded (MT1 and MT2).

Figure 3: Gender Differences in Motivations to Visit Environmentally Sustainable Restaurants (Mean Ranks for Significant Variables)



Source: Author

Note: The difference was statistically significant ($p < 0.05$).

Figure 3 illustrates the mean-rank differences between male and female respondents for the two motivational dimensions where statistically significant gender differences were identified. Female respondents achieved higher mean ranks than male respondents on both items, indicating a stronger association between environmentally sustainable restaurants and cultural as well as gastronomic experiences. For MT1 (*Green restaurants help me better understand the local culture*), female respondents reported a higher mean rank (55.05) than male respondents (45.53). The Mann–Whitney U test confirmed that this difference was statistically significant ($p = 0.003$), suggesting that women are more likely to perceive environmentally sustainable restaurants as a means of engaging with and learning about local culture. A similar pattern emerged for MT2 (*Green restaurants introduce me to new tastes of local food*). Female respondents again recorded a higher mean rank (55.56) compared with male respondents (44.66). The difference was statistically significant ($p = 0.004$), indicating that women more strongly associate environmentally sustainable restaurants with opportunities to explore new local culinary experiences. The results suggest that cultural learning and the discovery of local food flavors represent more salient motivations among female tourists. These findings are consistent with previous studies highlighting gender-

related differences in gastronomic motivations and experiential travel preferences (Kim & Eves, 2012; Björk & Kauppinen-Räsänen, 2016).

Figure 7: Gender Differences in Future Intentions to Choose Destinations with Green Restaurants

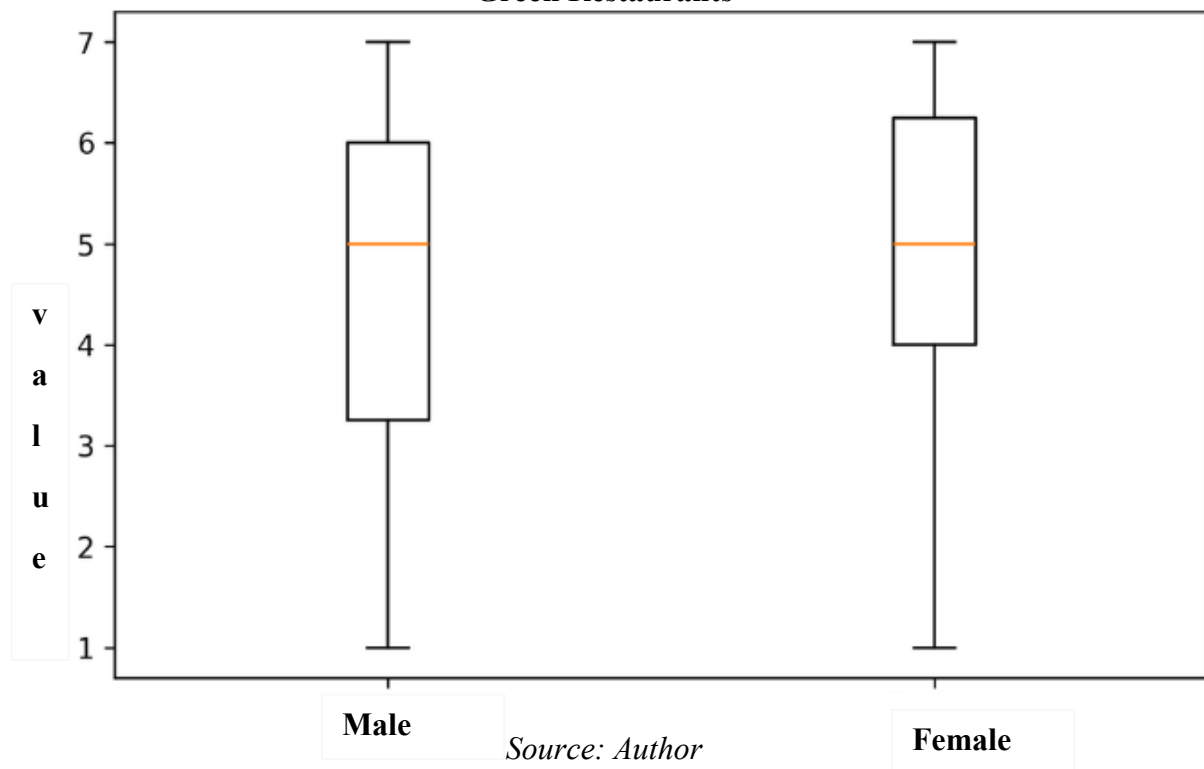


Figure X presents a boxplot illustrating gender differences in respondents' intentions to choose destinations with environmentally sustainable restaurants in the future due to their positive contribution to environmental protection. The distribution of responses indicates that female participants generally reported higher levels of agreement than male participants. The median score for females was higher, and the interquartile range was concentrated toward the upper end of the scale, suggesting a stronger intention to support destinations that offer green restaurants. Male respondents exhibited a slightly lower median and a wider distribution of responses across the scale, indicating greater variability in their intentions. In contrast, female respondents showed a greater concentration of responses at higher agreement levels (scores 5–7), reflecting a stronger orientation toward environmentally responsible tourism and dining choices. The boxplot suggests that women demonstrate a more favorable attitude toward selecting destinations with sustainable restaurants, supporting the assumption that gender may influence consumer motivations related to sustainable consumption (Sarmiento & El Hanandeh, 2018).

Conclusions

This study examined respondents' attitudes and motivations related to consumption in environmentally sustainable restaurants. The findings should be interpreted within the broader framework of green restaurants, which are characterized by environmentally responsible practices such as energy conservation, waste minimization, recycling, sustainable resource

management, and the use of locally sourced and seasonal ingredients. As such, green restaurants play a significant role in advancing circular tourism by promoting resource efficiency, reducing environmental impacts, and supporting local economic development.

The relatively high levels of agreement expressed by respondents suggest that tourists increasingly appreciate and support sustainable hospitality practices. This finding aligns with previous research indicating growing consumer willingness to patronize businesses that operate according to circular economy principles (Mostaghel & Chirumalla, 2021). Such tendencies reflect a broader transformation in consumer behavior, whereby traditional pleasure-oriented motivations are increasingly complemented by environmental awareness, social responsibility, and ethical considerations (Hwang & Lee, 2019). Consequently, selecting a green restaurant is not merely a culinary choice but also a reflection of personal commitment to environmental protection and community well-being. These findings further reinforce the importance of circular tourism as an effective approach to sustainable destination management and development (Kwok et al., 2016; Kirchherr et al., 2017; Buhalis & Sinarta, 2019).

The results also revealed greater consistency among female respondents, which may indicate a stronger appreciation of the experiential dimensions of gastronomy, including sensory enjoyment, cultural learning, and social interaction. Similar patterns have been reported in previous studies, where women were found to value gastronomic experiences as opportunities for enjoyment, education, and cultural engagement (Fields, 2003; Kim & Eves, 2012; Mazurek-Kusiak & Hawlena, 2026). By comparison, the broader range of responses observed among male participants may suggest a more diverse set of motivations, with some individuals placing greater emphasis on functional and practical aspects of dining experiences.

The practical implications of these findings are relevant for destination marketers, tourism managers, restaurant operators, and policymakers. The results highlight the need to develop green gastronomic products and experiences that resonate with both male and female tourists by combining sustainability attributes with meaningful cultural and emotional experiences. Promotional strategies should emphasize environmental stewardship, local food sourcing, and circular business practices in order to appeal to environmentally conscious consumers. At the same time, public policies can support the wider adoption of circular economy initiatives through incentives, regulations, and educational programs encouraging waste reduction, recycling, and sustainable procurement practices. In this way, gastronomic offerings grounded in circular consumption principles can contribute not only to sustainable tourism development but also to stronger destination branding, higher visitor satisfaction, and the promotion of long term pro environmental behavior. Furthermore, ensuring transparency, fairness, ethical sourcing, and respect for consumer rights can strengthen the credibility and social value of green restaurants within the tourism sector.

Future studies should extend this line of inquiry to different destinations and hospitality settings that have adopted or intend to adopt sustainable restaurant practices. Additional research could investigate how various demographic and socio-economic groups perceive circular economy initiatives and assess the role of sustainability education in shaping consumer decision-making processes. Moreover, further examination of the relationships among circular practices, consumer rights, and fair consumption could generate valuable insights for practitioners and policymakers seeking to design gastronomic experiences that are environmentally sustainable, socially responsible, and economically viable.

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FROM INDUSTRIAL CIRCULARITY TO WELL-BEING: ASSESSING THE SOCIAL EFFICIENCY OF THE CIRCULAR ECONOMY IN THE EU

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Abstract

This study investigates how effectively European Union Member States transform circular economy (CE) practices into social well-being, addressing a critical but underexplored dimension of circular transition research. While existing CE assessments primarily emphasize material flows, recycling performance, and resource productivity, far less is known about how circularity contributes to consumer-relevant and inclusive social outcomes.

Using an output-oriented Data Envelopment Analysis (DEA) framework under variable returns to scale, the study evaluates the social efficiency of CE across 27 EU countries, drawing on indicators of circular material use, material intensity, international recycling flows, self-perceived health, social inclusion, and real income. The results reveal substantial heterogeneity in social efficiency, showing that higher levels of circular activity do not automatically translate into stronger well-being outcomes for consumers.

Countries such as Denmark, Finland, Estonia, Ireland, Luxembourg, and Spain achieve full efficiency, indicating effective alignment between circularity practices, welfare structures, and socially inclusive outcomes. Conversely, several countries operate under decreasing returns to scale, suggesting that CE initiatives may dilute social effects and generate uneven distributional outcomes when implemented beyond their optimal capacity. Overall, the findings highlight the importance of policy coherence, institutional capability, and consumer-oriented governance in ensuring that circular economy strategies deliver inclusive and socially sustainable benefits.

Key words: *Industrial circularity, social well-being, sustainable integration, consumer relevance, efficiency*

Introduction

The transition toward a Circular Economy (CE) has become a central pillar of the European Union’s sustainability agenda, particularly following the adoption of the 2021 EU Climate Law and the European Green Deal, which commit Member States to achieving climate neutrality by 2050 and to decoupling economic growth from resource use (European Parliament and Council, 2021; European Commission, 2019). These commitments have been operationalized through successive Circular Economy Action Plans (CEAP), which aim not

only to improve resource efficiency and reduce waste but also to foster more resilient, equitable, and sustainable socio-economic systems (European Commission, 2020, 2022; Chioatto and Sospiro, 2023). As CE policies expand beyond waste management toward systemic transformations in production, consumption, and innovation, a growing question emerges: to what extent do industrial circularity efforts translate into improved social well-being?

In this context, the circular economy is increasingly understood not only as a production-side transformation but also as a consumer-facing transition, where issues of consumer protection, fairness, access, and inclusion become central. CE policies shape how consumers interact with goods and services by influencing affordability, product durability, access to repair and reuse, and exposure to environmental and economic risks. Consequently, the social outcomes of circularity are closely linked to how effectively CE practices are embedded within consumer-oriented governance frameworks, determining whether circular transitions enhance well-being broadly or generate uneven social effects.

In line with EU consumer and social policy frameworks, this study adopts a broad interpretation of consumer-relevant well-being. Rather than focusing narrowly on market transactions, consumer well-being is understood as encompassing key preconditions for effective consumer protection and empowerment in circular transitions, including economic security, access to essential services, and the capacity of households to benefit from durable, repairable, and affordable products. In this sense, health and social inclusion are treated as proxy indicators of consumer empowerment and welfare within circular economy systems.

Recent EU policy developments further reinforce the importance of this consumer-oriented perspective. In particular, Directive (EU) 2024/1799 on common rules promoting the repair of goods explicitly frames repair not only as an environmental strategy but as a core consumer right, linking circular economy performance with affordability, access to after-sales services, and legal enforceability. This policy shift highlights the growing recognition that circular economy transitions must deliver tangible consumer benefits, rather than remaining confined to upstream industrial or environmental performance.

Although the CE has traditionally been conceptualized through the 3R framework—reduce, reuse, recycle—recent scholarship argues for a broader understanding that incorporates redesign, remanufacturing, and recovery (Liu et al., 2021), or even more extensive R-strategies such as refuse, rethink, and repurpose within the 9R hierarchy (Kirchherr et al., 2017). These expanding conceptual boundaries reflect the recognition that circularity is not solely a technical or industrial process but also a societal transition involving behavioural change, institutional capacity, and shifts in value creation. Accordingly, CE is increasingly viewed through three interconnected dimensions—environmental, economic, and social—each contributing differently to sustainability transitions (Remeikienė et al., 2025). While the environmental and economic benefits of CE, such as reduced material consumption and improved resource productivity, are well documented (Mazur-Wierzbicka, 2021; Mohammed et al., 2021), the social implications of circularity remain less clearly understood, particularly from the perspective of consumers and distributional outcomes.

Emerging evidence suggests that circular systems may contribute to human well-being by improving living environments, reducing exposure to pollution, promoting repair and sharing cultures, supporting green employment, and fostering more inclusive consumption models (Moreau et al., 2017; Schröder et al., 2020). User-centred circular design, such as flexible and healthy interior systems, has been shown to enhance subjective well-being and health outcomes (Geldermans et al., 2019). Similarly, social life-cycle assessment frameworks demonstrate how circular products can influence social impacts across value chains (Tsalis et

al., 2022). Despite these insights, existing CE performance assessments overwhelmingly prioritise material flows, recycling rates, waste generation, and resource productivity, leaving open the question of how effectively countries convert circularity efforts into consumer-relevant social value, including fairness, inclusion, and protection.

This gap is particularly important because the circular economy is increasingly positioned not only as an environmental policy but also as a lever for promoting social resilience, equity, and quality of life at the consumer level. Without explicit attention to distributional effects, consumer protection mechanisms, and fairness considerations, CE strategies risk generating uneven social outcomes—benefiting certain groups while placing disproportionate costs or constraints on others. Nevertheless, empirical evidence on how efficiently countries transform industrial circularity into inclusive and consumer-relevant social well-being remains limited. There is still insufficient understanding of which countries achieve such transformations more effectively, what structural and governance factors shape these outcomes, and how CE policies interact with broader welfare and consumer protection systems.

Against this backdrop, this study contributes to the emerging research frontier by examining the social efficiency of the CE across EU-27 Member States. Moving beyond assessments focused solely on environmental and economic performance, the analysis evaluates the extent to which circular economy inputs are translated into improvements in subjective health, social inclusion, and living standards. By framing social efficiency as the capacity of circular economy practices to generate socially meaningful and consumer-relevant outcomes, the study aligns with calls in the literature to position the circular economy as a driver of inclusive social transformation rather than merely a tool for resource optimization. At the same time, it offers policy-relevant insights into how circular economy governance can be better aligned with consumer protection, fairness, and sustainable consumption objectives within the European Union.

Literature Review

Existing studies on the Circular Economy (CE) predominantly rely on indicator-based assessment frameworks, multi-criteria decision analysis (MCDA) methods, and composite indices to evaluate circularity performance, with a strong emphasis on environmental pressures, waste flows, and resource efficiency. These approaches have enabled researchers to capture multi-dimensional aspects of circularity, yet they typically prioritise measurable material outcomes over broader societal impacts. A significant line of research employs MCDA techniques to compare CE outcomes across countries, reflecting a growing interest in benchmarking progress and identifying structural drivers of performance differences. For instance, Štreimikienė et al. (2025) apply a CRITIC-weighted TOPSIS model to assess CE performance in the Baltic States and identify material productivity, waste-management efficiency, and secondary material use as key determinants of circularity. Similarly, Rađenović and Rajić (2024) use TOPSIS to rank EU member states based on circular material use, revealing higher performance among countries with stronger recycling infrastructures and mature regulatory frameworks. Grybaitė and Burinskienė (2024), employing the SAW method, further show that high-performing CE countries typically benefit from greater institutional capacity and long-term policy commitment. Collectively, these MCDA-based studies demonstrate the analytical value of multi-indicator assessments but remain largely centred on material flows and environmental criteria.

Beyond MCDA-based contributions, several empirical analyses offer a broader perspective on cross-country CE disparities. Nazarko et al. (2021) combine Data Envelopment Analysis with factor and cluster analysis to evaluate CE performance across 27 EU member states. Their findings show that numerous CE indicators cluster into five meta-groups—general waste recycling, special waste recycling, waste generation, circular material use, and CE-related jobs and investments—illustrating the high degree of inter-indicator correlation. Their results also indicate that CE leadership is domain-specific rather than universal, with different countries excelling in different recycling or material use indicators. Importantly, the study finds a strong link between GDP per capita and CE advancement, suggesting that economic capacity significantly shapes the feasibility of circular transitions. Complementing this view, Ūsas et al. (2022) develop an indicator system that captures circularity inputs, trade flows, and recycling processes, and identify Germany, Sweden, and the Netherlands as the most advanced CE performers. Their results highlight structural constraints faced by water-locked or newer EU member states and emphasise the critical role of monitoring systems and recycling infrastructure. In a similar vein, Fura et al. (2019), using multidimensional comparative analysis, show that the Benelux countries—Luxembourg, Belgium, and the Netherlands—are consistently among the most advanced in CE development, whereas countries such as Malta, Cyprus, Estonia, and Greece lag behind. Together, these contributions reinforce the conclusion that CE performance across the EU is highly heterogeneous and shaped by a combination of economic, infrastructural, institutional, and regulatory factors.

Broader European assessments further confirm the heterogeneity of CE performance across the EU. Radenović et al. (2023) shows that waste-management efficiency varies substantially across countries due to uneven infrastructure investment, differences in regulatory enforcement, and varying levels of administrative capacity. D’Adamo et al. (2024) complement these findings by showing that national circularity trajectories are strongly shaped by innovation capacity, technological modernization, and recycling-oriented industrial structures. Remeikienė et al. (2025) similarly document significant variation in resource productivity, circular material use, and waste generation, highlighting structural, institutional, and policy-related determinants as critical explanatory factors. Contributions linking CE to economic outcomes reinforce this pattern. Potkány et al. (2025) show that countries with stronger CE indicators tend to achieve higher levels of competitiveness, productivity, and value-added creation, while Milanović et al. (2022), using a DEA-based composite index, find that waste-management efficiency plays a substantial role in determining national CE performance. Yet, despite these contributions, the dominant focus of this literature remains on production systems, waste flows, and resource efficiency, reinforcing the prevalence of environmental and economic indicators in CE measurement.

Methodological reflections in the literature further emphasize the fragmented nature of CE measurement. dos Santos et al. (2022) highlight persistent inconsistencies in indicator selection, normalization procedures, and weighting schemes across MCDA-based CE studies, arguing that such inconsistencies hinder the comparability and robustness of CE performance evaluations. They also emphasize that social indicators continue to be markedly underrepresented in CE assessments, despite increasing acknowledgment that circularity has implications extending beyond material efficiency. This observation is echoed in broader critiques of CE research: Moreau et al. (2017) argue that circularity cannot be fully understood without accounting for social and institutional dynamics, such as behavioural norms, governance systems, labour conditions, and inequality structures. Schröder et al. (2020) similarly contend that CE strategies need to be aligned with human development goals,

suggesting that circular initiatives should be designed not only to improve resource efficiency but also to promote equity, social welfare, and human capabilities.

Recent years have witnessed growing interest in the social implications of circular practices. Nikonorova et al. (2020) emphasize the importance of incorporating social well-being indicators into CE assessments, while Bianchini et al. (2022) propose a structured framework for evaluating social sustainability within CE contexts, illustrating how social criteria can complement environmental indicators in assessing circular transitions. Tsalis et al. (2022) move this discussion forward by developing a social life-cycle assessment framework adapted to circular products, thereby demonstrating methodological pathways for quantifying social impacts across entire product chains. Additional insights come from Geldermans et al. (2019), who explore how circular interior design configurations, particularly flexible infill systems, can influence human health and well-being by shaping indoor comfort, adaptability, and user experience. Such findings illustrate that circularity can affect outcomes at the operational and everyday life level, beyond macro-level performance metrics.

Other recent contributions broaden the social dimension of CE. Skare et al. (2024) examine how research and development activities within a CE framework may contribute to reducing inequality and enhancing societal well-being across the EU, positioning CE as a potential tool for promoting social cohesion. Sharma and Bangur (2025) highlight the public health benefits associated with circular practices, suggesting that reduced pollution, safer material cycles, and improved environmental quality may collectively strengthen population health. At the consumer level, Petreca et al. (2025) show that circular textile systems influence psychological and experiential aspects of well-being, pointing to the importance of understanding CE impacts not only at macro scales but also within individual consumption experiences. Methodological developments have also supported the integration of social metrics into CE research: Ahmadi et al. (2017) demonstrate that complex social criteria can be systematically weighted using the Best–Worst Method (BWM), offering a structured approach for incorporating social dimensions into CE evaluations. Finally, Calisto et al. (2024) argues that transitioning toward a circular society requires explicit attention to justice, inclusivity, and broader socio-economic transformation, as resource efficiency alone is insufficient to achieve socially sustainable outcomes.

Taken together, these studies reveal a consistent pattern: CE assessments remain largely dominated by indicators related to material flows, waste-management efficiency, and resource productivity, while the social implications of circular practices—including well-being, inclusion, equity, and health—receive comparatively limited empirical attention. Although recent studies have begun to explore inequality reduction, human development, public health improvements, consumer well-being, and broader social sustainability within CE contexts, these contributions remain fragmented and only loosely connected to mainstream CE performance frameworks. Systematic analyses that integrate CE indicators with measurable social well-being outcomes are still scarce, leaving an important gap in understanding how effectively countries translate circularity efforts into social value. The present study seeks to contribute to this emerging discussion by proposing a framework that evaluates CE performance alongside social well-being indicators across EU member states, offering a broader and more holistic perspective on the societal dimension of circular economy practices.

Research Method

This study evaluates the ability of EU 27 member states to transform circular-economy–related resource flows into social well-being outcomes. For this purpose, a non-parametric

Data Envelopment Analysis (DEA) framework is employed. DEA is particularly suitable for this research because it enables the assessment of relative efficiency across multiple decision-making units (DMUs) when several inputs and outputs coexist without requiring a predefined functional form (Charnes et al., 1978).

Given that countries differ considerably in economic size, industrial composition and demographic structure, the analysis uses both Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) models to capture overall technical efficiency and pure technical efficiency (TE), respectively. Scale efficiency (SE) is then derived as the ratio of CRS to VRS scores, allowing identification of whether inefficiency stems from suboptimal scale or managerial/technical factors. An output-oriented specification is adopted in the analysis. This choice reflects the conceptual focus of the study: the objective is not to reduce circular economy inputs, but rather to assess how effectively these inputs are transformed into desirable social outcomes such as social inclusion, subjective health, and economic well-being.

The output-oriented DEA models used in this study follow the standard formulations introduced by Charnes, Cooper, and Rhodes (1978) for the constant returns to scale (CRS) model and by Banker, Charnes, and Cooper (1984) for the variable returns to scale (VRS) model. The CRS (CCR) model captures overall technical efficiency, whereas the VRS (BCC) model isolates pure technical efficiency while allowing for variable returns to scale. Scale efficiency is subsequently derived following Banker et al. (1984).

For each DMU, the output-oriented VRS model is formulated in equation 1 (Banker et al., 1984):

$$\begin{aligned}
 & \max_{\phi, \lambda_j} \quad \phi \\
 & \text{s.t.} \quad \sum_{j=1}^n \lambda_j x_{ij} \leq x_{io}, \quad i = 1, \dots, m, \\
 & \quad \sum_{j=1}^n \lambda_j y_{rj} \geq \phi y_{ro}, \quad r = 1, \dots, s, \\
 & \quad \sum_{j=1}^n \lambda_j = 1, \\
 & \quad \lambda_j \geq 0, \quad j = 1, \dots, n.
 \end{aligned} \tag{1}$$

The VRS technical efficiency score is computed as in equation 2:

$$\text{VRS_TE}_o = \frac{1}{\phi_o^*}. \tag{2}$$

A DMU is VRS-efficient when $\phi^* = 1$.

The CRS model is derived by removing the convexity constraint $\sum_{j=1}^n \lambda_j = 1$ (Charnes et al., 1978):

$$\begin{aligned} \max_{\phi, \lambda_j} \quad & \phi \\ \text{s.t.} \quad & \sum_{j=1}^n \lambda_j x_{ij} \leq x_{io}, \\ & \sum_{j=1}^n \lambda_j y_{rj} \geq \phi y_{ro}, \\ & \lambda_j \geq 0. \end{aligned} \tag{3}$$

The resulting efficiency score is denoted as CRS_TE.

Scale efficiency is computed as in equation 4 :

$$SE_o = \frac{CRS_TE_o}{VRS_TE_o}. \tag{4}$$

Returns to scale (RTS) are determined by standard DEA procedures:

- CRS when $CRS_TE = VRS_TE$,
- IRS when the sum of optimal $\lambda_j < 1$,
- DRS when the sum of optimal $\lambda_j > 1$.

These indicators allow the study to differentiate between inefficiencies arising from policy, structural factors, and scale mismatches.

Furthermore, to deepen the interpretation of the DEA results and to identify underlying structural patterns among EU member states, a K-means cluster analysis (k=3) was conducted using the three efficiency indicators (CRS-TE, VRS-TE, and SE). The purpose of this procedure is to group countries that exhibit similar efficiency characteristics, allowing for a clearer understanding of performance heterogeneity across the region. The clustered heatmap was subsequently organized according to these K-means groupings and further sorted within each cluster by CRS scores. This integrated approach improves interpretability by visually linking efficiency intensity with the structural similarity of countries, thereby providing a more nuanced assessment of cross-country efficiency dynamics.

Selection of Inputs and Outputs

In this study, to ensure cross-country standardization and comparability, all variables were obtained from Eurostat, and the analysis uses data from the year 2023. The selected indicators capture three fundamental dimensions of the analysis: (i) industrial circularity, (ii) material efficiency, and (iii) socioeconomic well-being. Table 1 summarizes the input and output variables used in the Data Envelopment Analysis (DEA). Three indicators representing material circularity and resource processing constitute the input set, while three indicators reflecting socioeconomic well-being form the output set, enabling an assessment of how effectively EU member countries convert circular economy practices into social outcomes.

Table 1. Input and Output Variables Used in the DEA Model

Type	Code	Variable Name	Description / Definition	Expected Direction
Input	X1	Circular Material Use Rate (%)	Share of material inputs coming from recycled materials in the economy. Indicates the level of circularity and secondary material integration.	Higher values indicate better circularity (desirable input).
Input	X2	Domestic Processed Output per Capita (tonnes)	Total material processed domestically per person, reflecting the economy's material intensity. Higher values imply greater environmental pressure.	Lower values are preferred; treated as an undesirable input (transformed as $1/X2$ in the model).
Input	X3	Exports of Waste for Recovery/Recycling (tonnes per capita)	Amount of waste exported for recycling, capturing the country's circular economy infrastructure and international circularity performance.	Higher values indicate better circular economy performance (desirable input).
Output	Y1	Social Inclusion (100- Severe material deprivation rate by degree of urbanization %)	Percentage of population not experiencing severe material deprivation. Reflects social well-being and living standards for consumers	Higher values indicate higher social well-being.
Output	Y2	Self-Perceived Health (Very Good/Good, %)	Share of the population aged 16+ reporting very good or good health. Captures subjective well-being and quality of life.	Higher values indicate better health outcomes.
Output	Y3	Real GDP per Capita (EUR)	Income-based measure of economic welfare and living standards, adjusted for price levels.	Higher values indicate stronger economic well-being.

Circular Material Use Rate (X1) and Exports of Waste for Recycling (X3) are treated as desirable inputs, whereas Domestic Processed Output per capita (X2) is considered an undesirable input due to its association with higher material throughput and resource intensity. To ensure model consistency, X2 is transformed using its inverse value ($1/X2$), allowing lower material output to be reflected as higher input efficiency. Together, these three indicators capture key dimensions of industrial circularity and material flow efficiency, representing different stages of the circular economy cycle—resource recirculation, material processing intensity, and cross-border recovery activities. Collectively, they reflect the structural capacity of countries to operate within a circular production system.

The output variables—Social Inclusion (Y1), Self-Perceived Health (Y2), and Real GDP per capita (Y3)—represent complementary aspects of social and economic well-being. The social dimension is mainly addressed at an aggregate level, with attention to distributional effects and the specific impacts on consumers. These indicators enable an assessment of how effectively circular economy inputs are translated into societal benefits. By combining resource-oriented inputs with human-centered outputs, the model allows for a holistic evaluation of the social efficiency of circular economy performance, in line with current sustainability and well-being frameworks.

Table 2. Descriptive Statistics of Input and Output Variables

Variable	Description	Obs	Mean	Std. Dev.	Min	Max
X1	Circular Material Use Rate (%)	27	10.28	7.11	1.30	30.60
X2	Domestic Processed Output per Capita (tonnes)	27	0.115	0.0335	0.0608	0.1798
X3	Exports of Waste for Recovery/Recycling (tonnes per capita)	27	0.384	0.269	0.080	1.020
Y1	Social Inclusion (% not severely deprived)	27	94.31	3.38	83.70	99.00
Y2	Self-Perceived Health (% good/very good)	27	67.47	8.09	48.90	80.10
Y3	Real GDP per Capita (EUR)	27	31,898.89	20,783.14	9,140	93,670

Table 2 shows notable cross-country variation in both inputs and outputs. Circular Material Use (X1) ranges widely from 1.3% to 30.6% (mean 10.28%), indicating uneven adoption of secondary materials. Waste exports for recovery (X3) also vary substantially (0.08–1.02 tonnes per capita). The undesirable input, Domestic Processed Output (X2), shows a narrower range (0.06–0.18 tonnes).

On the output side, Social Inclusion (Y1) is generally high but still spans from 83.7% to 99%. Self-perceived health (Y2) shows greater dispersion (48.9%–80.1%), while GDP per capita (Y3) exhibits the widest gap—from €9,140 to €93,670. These variations highlight strong heterogeneity among EU countries and support the use of an efficient framework to assess how effectively circular inputs are transformed into social well-being.

Table 3. Variables Correlation Matrix

Variables	X1	X2	X3	Y1	Y2	Y3
X1 – Circular Material Use Rate	1.0000					
X2 – Domestic Processed Output (1/X2)	-0.1247	1.0000				
X3 – Waste Exports for Recovery	0.3264	-0.3742	1.0000			
Y1 – Social Inclusion	0.1110	-0.4283	0.3769	1.0000		
Y2 – Self-Perceived Health	0.2096	0.0789	-0.2677	-0.2923	1.0000	
Y3 – GDP per Capita	0.1645	-0.5158	0.1155	0.3695	0.4090	1.0000

The correlation matrix in Table 3 indicates that the relationships among the variables are generally weak to moderate in magnitude. Most coefficients fall well below 0.40, suggesting that the input and output variables capture distinct dimensions of circularity and well-being. The only moderately strong associations are the negative relationship between X2 (Domestic Processed Output) and Y3 (GDP per capita), and the positive relationship between Y2 (Self-Perceived Health) and Y3, both of which align with expected economic and social patterns. Overall, the low-to-moderate correlations confirm that no variables are excessively related, and the dataset does not exhibit multicollinearity concerns. This indicates that the variables are suitable for inclusion in the DEA model and contribute unique information to the efficiency analysis.

Results

The DEA results presented in Table 4 reveal substantial heterogeneity in the ability of EU member states to convert circular-economy-related inputs into socioeconomic outcomes. Under the output-oriented VRS specification, twelve countries—Denmark, Estonia, Finland, Greece, Ireland, Italy, Luxembourg, Malta, Poland, Portugal, Romania, and Spain—achieve a pure technical efficiency score of 1, indicating that they operate on the efficient frontier once scale effects are removed. These countries demonstrate the strongest capability to translate

circular inputs such as circular material use, domestic processed output, and recycling-related flows into higher levels of social inclusion, better self-perceived health, and higher income levels.

When the CRS assumption is imposed, the same set of countries remains fully efficient, suggesting that they are not only technically efficient but also operate at an optimal scale. This dual efficiency indicates a highly effective transformation mechanism between industrial circularity and consumer-level well-being in these economies.

In contrast, several countries exhibit notable gaps between CRS and VRS efficiency levels. For example, Austria, Slovenia, Slovak Republic, Latvia, and France show relatively high VRS efficiency (0.93–0.99) while maintaining substantially lower CRS scores (0.52–0.69). This divergence implies that these countries possess adequate technological capabilities but experience scale inefficiencies, which prevent them from operating on the global frontier. Their inefficiency is therefore driven not by poor input–output conversion but by suboptimal production scale.

The scale efficiency estimates confirm this pattern: the lowest values are observed in Slovenia (0.53), Latvia (0.58), Slovak Republic (0.62), Austria (0.69), and France (0.72). These results indicate that these countries could improve overall efficiency by adjusting the scale at which circular-economy activities are implemented.

The Returns to Scale (RTS) classification provides additional insight into the nature of scale deviations. Most inefficient countries operate under Decreasing Returns to Scale (DRS), meaning that their current scale is larger than optimal and that downsizing or restructuring resource-use patterns would yield efficiency gains. In contrast, only Belgium and Malta operate under Increasing Returns to Scale (IRS), implying that an expansion of circular-economy capacity—through greater recycling infrastructure, increased circular material flows, or larger CE markets—would enhance their efficiency. Countries classified as CRS (including Denmark, Finland, Estonia, Luxembourg and Spain) already operate at the optimal scale.

Overall, the results indicate that while a group of EU economies demonstrates efficient transmission of circular-economy capabilities into social well-being, many others face structural scale constraints. The findings highlight the importance of considering both technological efficiency and scale effects when assessing the social efficiency of circular-economy performance.

Table 4. DEA Efficiency Scores for EU Member States (CRS, VRS and Scale Efficiency)

Country	CRS_TE	VRS_TE	Scale Efficiency	RTS
Austria	0.6427	0.9381	0.6851	DRS
Belgium	0.6444	0.9563	0.6739	IRS
Bulgaria	0.6718	0.9073	0.7405	DRS
Croatia	0.6884	0.9967	0.6907	DRS
Cyprus	0.8691	0.9963	0.8723	DRS
Czechia	0.6648	0.9737	0.6828	DRS
Denmark	1.0000	1.0000	1.0000	CRS
Estonia	1.0000	1.0000	1.0000	CRS
Finland	1.0000	1.0000	1.0000	CRS
France	0.6845	0.9551	0.7166	DRS
Germany	0.7373	0.9582	0.7695	DRS
Greece	1.0000	1.0000	1.0000	CRS
Hungary	0.6132	0.9643	0.6359	DRS
Ireland	1.0000	1.0000	1.0000	CRS
Italy	1.0000	1.0000	1.0000	CRS

Latvia	0.5754	0.9872	0.5829	DRS
Lithuania	0.6617	0.9892	0.6689	DRS
Luxembourg	1.0000	1.0000	1.0000	CRS
Malta	0.9034	1.0000	0.9034	IRS
Netherlands	0.6588	0.9616	0.6851	DRS
Poland	0.9635	1.0000	0.9635	DRS
Portugal	0.9870	1.0000	0.9870	DRS
Romania	1.0000	1.0000	1.0000	CRS
Slovak Republic	0.5749	0.9245	0.6219	DRS
Slovenia	0.5264	0.9969	0.5281	DRS
Spain	1.0000	1.0000	1.0000	CRS
Sweden	0.6792	0.9869	0.6882	DRS

CRS: Constant Returns to Scale → optimal scale

DRS: Decreasing Returns to Scale → scale too large (downsizing efficiency)

IRS: Increasing Returns to Scale → scale too small (scaling up efficiency)

In this study, the reference set frequency was identified to determine which efficient units shape the frontier and serve as benchmarks for underperforming countries as well. This measure highlights the most influential performers and provides insight into which countries' circularity–well-being transformation patterns offer the strongest policy-learning potential.

The reference set frequency (Figure1) provides critical insights into which EU Member States serve as efficiency benchmarks in transforming circular economy inputs into social well-being outcomes. The results indicate that Luxembourg and Ireland each appear 14 times, and Poland appears 10 times, in the reference sets of inefficient countries, making them the most influential benchmark countries in the model. This pattern suggests that these countries form the core of the DEA efficient frontier and represent the most effective models of converting circularity indicators into improved well-being.

A second group of benchmark countries, Italy and Romania, exhibit moderate peer frequency, being referenced only a few times. Several countries, including Spain, Portugal, Malta, Greece, Finland, Estonia and Denmark appear only once in the reference sets. While technically efficient, their limited benchmarking role suggests that their efficiency patterns are either context-specific or less transferable to other countries with different structural profiles.

Figure 1. Reference Set Frequency (Peer Frequency)

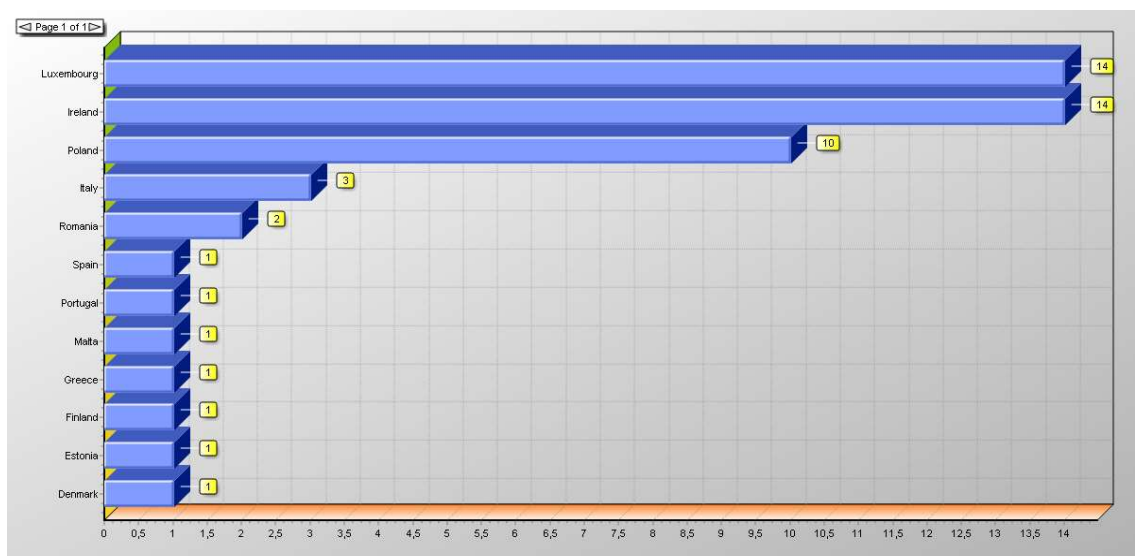
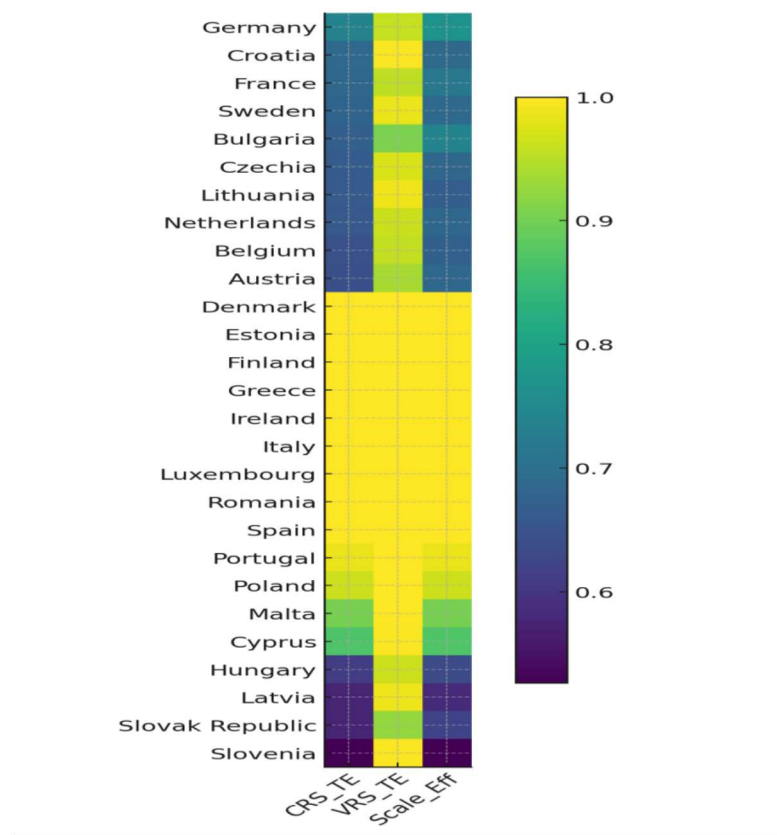


Figure 2. Clustered Heatmap of DEA Efficiency Scores

In Figure 2, the heatmap presents clear cross-country differences in the ability of EU members to convert circular economy inputs into social well-being outcomes. A K-means cluster analysis ($k = 3$), based on CRS, VRS and scale efficiency scores, was used to structure the visual ordering of countries. Countries were grouped according to similarity in efficiency profiles, and the heatmap was sorted first by cluster membership and then by CRS efficiency within each cluster. This approach allows the visualization to reflect both efficiency intensity and the underlying structural grouping.

The resulting clusters reveal three distinct performance patterns. Denmark, Finland, Ireland, Luxembourg and Spain constitute the high-performing group, exhibiting strong results across all efficiency measures. Austria, Belgium, France, Germany and the Netherlands form a medium-efficiency cluster, where high VRS scores but lower CRS and scale efficiency suggest suboptimal scale in circular economy implementation. A third cluster—including Latvia, Hungary, Slovenia and the Slovak Republic—shows the lowest efficiency levels, indicating structural and scale-related constraints in transforming circular economy practices into social outcomes.

Discussion

The results of this study reveal that the relationship between Circular Economy (CE) performance and social well-being across EU Member States is far from uniform. While CE policies have traditionally been justified through environmental and economic gains, the

findings demonstrate substantial cross-country variation in the capacity to convert circularity inputs into improved living standards, subjective health, and social inclusion. This confirms a growing consensus in the literature that the CE cannot be assessed solely as a technical system of material loops, but must instead be understood as a broader socio-economic transformation process that directly affects consumers and social outcomes (Moreau et al., 2017; Schröder et al., 2020).

One of the central insights of the efficiency analysis is that high levels of circular economy activity do not automatically translate into higher social well-being or consumer-relevant benefits. Countries such as Germany and the Netherlands—characterized by advanced recycling infrastructures, high circular material use rates, and long-standing CE policies—exhibit notable inefficiencies in transforming circularity inputs into social outcomes. Despite their strong industrial and technological capacity, these countries do not achieve proportional improvements in indicators such as subjective health or social inclusion. This suggests a disconnect between technical circularity performance and the lived social experience of circular transitions, including how benefits and costs are distributed across consumers. In contrast, countries such as Ireland and Luxembourg, which may not lead in material recycling volumes to the same extent, demonstrate substantially higher efficiency in translating circular economy efforts into well-being improvements. These patterns challenge the conventional assumption that environmentally advanced economies are automatically leaders in socially inclusive circular transitions. Instead, the findings support arguments by Bianchini et al. (2022) and Nikonorova et al. (2020), who emphasize that the social benefits of circularity depend critically on how CE practices are embedded within welfare systems, labour markets, consumer cultures, and behavioral norms.

The study further underscores the importance of policy scale and targeting in shaping the social and consumer-level outcomes of CE initiatives. Countries operating under decreasing returns to scale appear to implement CE measures at levels that exceed their effective capacity to generate proportional social benefits. From a consumer perspective, such scale inefficiencies may translate into higher costs, limited access to circular products or services, and uneven distribution of benefits, particularly for vulnerable or lower-income groups. Broad, undifferentiated CE strategies may therefore dilute social returns when they are not sufficiently aligned with sectoral priorities, local socioeconomic conditions, and consumer protection mechanisms. These findings resonate with concerns raised in methodological and policy-oriented reviews (e.g., dos Santos et al., 2022) regarding fragmentation in CE implementation and the mismatch between policy ambition and institutional capacity.

From a consumer-protection perspective, these scale inefficiencies carry important distributional implications. Countries operating under decreasing returns to scale may face higher compliance costs, limited access to repair and reuse services, or uneven availability of circular products and services, potentially placing disproportionate burdens on lower-income and vulnerable consumer groups. Such dynamics suggest that beyond technical efficiency, circular economy governance must explicitly address affordability, accessibility, and fairness in order to ensure inclusive consumer welfare outcomes and to prevent circular transitions from reinforcing existing social inequalities.

The scale inefficiencies observed across several EU Member States suggest that the societal impact of the circular economy depends not only on technical or infrastructural capacity, but also on the appropriate calibration of governance frameworks. When circular economy activities are deployed beyond their optimal scale—across wide geographical areas or heterogeneous sectors—their contribution to social well-being and consumer fairness becomes less effective. For example, the broad industrial structures and high material-use

intensity of Austria and France appear to reduce the marginal social returns of CE investments, while in smaller economies such as Slovenia and the Slovak Republic, the dispersion of CE initiatives across multiple sectors leads to similar inefficiencies. These patterns indicate that more targeted, locally grounded, and sector-prioritised policy designs—combined with consumer-oriented regulatory instruments—may enhance both resource-use efficiency and socially inclusive outcomes.

A further implication of the results is that economic development alone is insufficient to guarantee socially effective and fair circular transitions. Several high-income Member States, despite their advanced CE infrastructures and technological capabilities, display limited efficiency in converting circular inputs into well-being outcomes that are meaningful for consumers. This finding aligns with the observation by Calisto Friant et al. (2024) that resource efficiency gains do not automatically translate into social justice, inclusivity, or improved quality of life. To realize the full societal potential of the circular economy, the social dimension must be explicitly integrated into CE strategies through governance mechanisms that prioritize consumer protection, address distributional effects, and ensure equitable access to the benefits of circular production and consumption systems.

Conclusions

This study assessed the efficiency with which EU Member States transform circular economy (CE) inputs into social well-being outcomes using a Data Envelopment Analysis framework. The results demonstrate that CE efforts are not uniformly converted into social benefits across the European Union. Countries such as Denmark, Finland, Ireland, Luxembourg, Estonia, and Spain achieve full efficiency, indicating that their circular economy infrastructures are effectively aligned with improvements in subjective health, social inclusion, and living standards.

In contrast, several countries—most notably Germany, the Netherlands, Austria, and France—exhibit significant inefficiencies, suggesting that strong industrial or environmental CE performance does not automatically generate proportional social gains. These findings reinforce the growing view that the social value of the circular economy depends not merely on technical or material performance, but on how circular practices are embedded within broader behavioral, institutional, welfare, and consumer-related structures. In this sense, circular transitions that are not adequately aligned with consumer access, affordability, and protection may deliver limited improvements in lived social outcomes.

Scale effects play a particularly important role in shaping these results. Countries operating under decreasing returns to scale often implement CE policies at a scope or intensity that exceeds their capacity to translate such efforts into social benefits. When circular initiatives are dispersed across too many sectors or wide geographical areas without sufficient coordination, resources become diluted and the social returns of circularity diminish. From a consumer perspective, such scale mismatches may also result in uneven distribution of benefits and costs, potentially placing disproportionate burdens on certain consumer groups rather than enhancing inclusive well-being. These patterns suggest that more targeted, context-specific, and locally grounded CE strategies—focused on priority sectors, vulnerable groups, or specific regions—can generate higher social returns by aligning implementation scale with institutional capacity and consumer needs.

The study also yields clear policy implications. Strengthening the social benefits of circular transformation requires closer alignment between circular economy policies and consumer protection frameworks, social programmes, behavioral incentives, and community-

level initiatives. Ultimately, the extent to which circularity contributes to societal well-being depends not on the scale of activities alone, but on the efficiency, coherence, and strategic design of governance frameworks that connect circular practices to fairness, consumer inclusion, and broader social outcomes. Without such alignment, circular economy transitions risk achieving environmental objectives while falling short of their social and consumer-oriented potential.

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SEGMENTED LIABILITY IN ONLINE LEGAL ADVICE: A RECONCEPTUALIZATION OF RESPONSIBILITY TOWARD THE DIGITAL CONSUMER

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Abstract

The accelerated digitalization of legal services has profoundly reshaped the way legal information is produced, accessed, and perceived by users. Online platforms have become, for an increasing number of individuals, the primary point of access to legal consultancy. Within this emerging ecosystem, users, often positioned as digital consumers lacking critical evaluative resources, are exposed to new forms of legal risk generated by asymmetries of expertise and by the opacity of algorithmic mechanisms that influence content visibility and perceived credibility.

In this context, classical models of civil liability centered on the author–user relationship prove inadequate to explain the emergence of harm in digital environments. This paper advances a segmented liability model grounded in the interaction between the author of legal content, the digital platform, and the algorithmic architecture, each contributing in a distinct manner to the formation of legal risk.

The study adopts a comparative perspective, examining the regulatory frameworks of Romania and the Republic of Moldova. It highlights the transformative role of the Digital Services Act and demonstrates that legal harm may arise not only from human error, but also from algorithmic mechanisms of automated validation and dissemination of information.

The segmented liability model offers an analytical framework capable of integrating civil law principles with European digital governance and of supporting a preventive approach to technological risks. The conclusions emphasize the model’s potential to inform future doctrinal and legislative developments concerning legal responsibility in digital environments, particularly within the Eastern European legal space.

Key words: online legal advice; segmented liability; digital consumer; digital platforms; algorithms; Digital Services Act (DSA); legitimate trust.

Introduction

The accelerated digitalization of legal services has reshaped how legal information is produced, organized, and accessed, with digital platforms becoming, for a growing audience,

the primary point of contact with law. Within this informational ecosystem (Floridi, 2014), the digital consumer faces trust-based risks: difficulty verifying response accuracy and the opacity of technical distribution criteria, which can create an appearance of authority and turn informational errors into legal harm (Pasquale, 2015; Helberger et al., 2022).

These risks are illustrated by recent judicial incidents, such as *Mata v. Avianca* (2023) in the United States, where unacknowledged use of generative algorithms led to fabricated legal authorities being presented as evidence—showing that digital error can translate directly into material and professional harm—and *Moffatt v. Air Canada* (2024), which underscores a platform’s liability for information mediated algorithmically.

The European Union has responded through the Digital Services Act (Regulation (EU) 2022/2065), shifting the discussion from technological neutrality to duties of diligence and transparency regarding content-distribution architecture. In this framework, the Romania–Republic of Moldova comparison is particularly relevant: Romania operates under the DSA (directly applicable), while the Republic of Moldova remains largely *ex post*, yet offers civil-law reference points (especially Article 2018 of the Civil Code) capable—through evolutionary interpretation—of supporting digital-consumer protection.

Practically, a key tension lies in the gap between widespread exposure to such technologies and the scarcity of visible litigation, suggesting difficulties in identifying the pertinent actor and characterizing technological causal chains. Consistent with ECO4ALL’s objectives, the analysis proceeds from the premise that fairness in digital markets depends on an accountability framework capable of preventing the externalization of informational-error costs onto the vulnerable consumer.

Against this background, the paper asks whether classical civil-liability models centered on the author–user relationship can adequately explain harm in online legal advice, or whether a reconceptualization is required for multi-actor digital environments. The working hypothesis is that a focus exclusively on the author’s conduct is insufficient, as platforms and algorithmic mechanisms play a decisive role in shaping user trust and generating legal risk.

The study’s original contribution is a model of segmented liability, grounded in the interaction between the author of legal content, the digital platform, and algorithmic architecture, as an analytical tool integrating civil law with European platform regulation. Through a comparative analysis of Romanian and Moldovan normative frameworks, the paper highlights the model’s potential to provide a coherent approach for protecting the digital consumer and managing legal risks online.

Methodology and theoretical framework

The paper adopts a predominantly normative and doctrinal approach, aiming to formulate an analytical model of legal liability applicable to online legal advice, at the intersection of civil law, consumer protection, and the governance of digital platforms.

Methodologically, the analysis relies on a systematic interpretation of the relevant European Union legal framework—with particular focus on the Digital Services Act (Regulation (EU) 2022/2065)—and on integrating specialized literature on platform governance, informational risk, and digital-consumer vulnerability. The theoretical framework proceeds from the premise that legal harm in the digital environment may result not only from the content provided, but also from how it is organized, amplified, and validated through platformized architectures and algorithmic mechanisms (Floridi, 2014; Busch & De Franceschi, 2021; De Bruyne, Dheu & Ducuing, 2023). The assessment of liability is

structured around the interaction among actors who contribute to the production and circulation of legal information online.

A comparative method is used to highlight structural and functional differences between Romania and the Republic of Moldova. Romania, as an EU Member State, operates within an integrated framework shaped by digital governance (including ex ante platform obligations), whereas the Republic of Moldova—though within the same civil-law tradition—remains in a process of normative convergence, without a fully functional DSA equivalent. The comparison identifies regulatory asymmetries relevant to Eastern Europe and provides a “mirror-effect” analysis: Romania illustrates the integration of the European digital-governance layer, while the Republic of Moldova tests the capacity (and limits) of civil law’s organic adaptation in the absence of an equivalent digital normative apparatus.

As regards scope, the inquiry does not compare administrative enforcement effectiveness, institutional capacity, or domestic judicial practice in volume and trends (quantitative data). Rather, it offers a doctrinal-normative comparison of mechanisms for attributing liability and protecting the digital consumer. The “constant” element is the civil-law matrix, centered on civil liability and legitimate trust; the “EU-specific” element is the DSA’s ex ante layer of obligations, which is not fully transferable outside the Union and is therefore treated, for the Republic of Moldova, as a guiding reference rather than a directly applicable standard.

The study remains predominantly normative and does not pursue empirical validation or quantitative analysis of litigation involving AI or online legal advice. Complementarily, it selectively refers to a limited number of recent jurisprudential reference points and factual incidents, used solely for illustrative purposes: to exemplify risk typologies associated with the three tiers (author–platform–algorithm) and to make the model’s application intelligible in concrete situations. These examples are not invoked as empirical validation and do not support generalizations; they serve to conceptually anchor the normative argument on allocating responsibility within a technological causal chain.

The analysis is limited to civil liability and the consumer-protection dimension regarding legal information provided or mediated digitally. It does not aim to exhaustively address all potentially relevant legal regimes (e.g., criminal law, professional/disciplinary liability, public-law enforcement mechanisms/regulatory sanctions), but rather to construct an analytical framework for the civil-law characterization of risks.

The Transformation of Legal Advice in the Online Environment and the New Status of the Digital Consumer

The digitalization of legal services has not only changed the channels through which legal information reaches the public, but also the nature of that information and the way it is perceived. Within the environment of digital platforms, online legal advice no longer appears exclusively as a clearly delimited professional service, but rather as a heterogeneous set of answers, opinions, and recommendations, delivered across diverse technical and communicative contexts. This transformation places online legal advice at the intersection of public information, legal counselling, and digital architecture, raising new issues regarding legal qualification and the attribution of liability.

Before examining the legal regime applicable to platforms, it is necessary to clarify the nature of online legal advice as an informational practice: what type of content it is, what expectations it generates, and through which technical mechanisms it comes to be perceived as influential.

This section successively highlights the hybrid character of such advice, the role of algorithms in amplifying risk, the function of platforms as active informational actors, and the position of the digital consumer as a vulnerable subject within this ecosystem.

Online Legal Advice: Conceptual Definition and Methodological Framework

In a broad sense, online legal advice denotes the set of legal information, opinions, and recommendations provided through digital platforms. It is distinct both from general legal information and from traditional professional legal advice; instead, it occupies an intermediate zone, marked by a variable degree of personalization and a significant impact on users' decisions.

This intermediate positioning gives online legal advice a hybrid character that is relevant for liability analysis. A user may rely on a legal response without a contractual relationship or professional guarantees as to accuracy, thereby increasing the likelihood of harm.

Accordingly, a piece of content's legal relevance depends not only on what it conveys, but also on the function it performs in the digital context, its degree of adaptation to the user's situation, and the likelihood that the user will treat it as a basis for a legal decision. As responses are perceived as signaling authority or expertise, the associated legal risk increases proportionally.

To capture these differences in impact, the analysis proposes an operational typology of the main forms of online legal advice, summarized in Table 1. The typology maps a progression from general information—with low legal impact—to tailored or automated counselling, where both the risk of harm and the complexity of liability increase significantly.

The typological criteria draw on the literature on platform governance, informational risk, and trust dynamics in digital environments, adapted to the specificities of legal content—where the consumer occupies a structurally vulnerable position in cognitive terms.

Table 1. Typology of Online Legal Advice

Type of Legal Content	Core Feature	Degree of Personalization	Risk Level for User	Liability Potential
General Information (articles, FAQs)	Explains general legal concepts	Low	Low	Minimal
Informal Opinion or Guidance	Generic, non-tailored responses	Low–Medium	Variable	Moderate
Contextualized Recommendation	Partially adapted to a specific situation	Medium	Significant	High
Individualized legal advice	Case-specific analysis	High	High	High
AI-generated content	Automated responses without human oversight	Variable	High (unpredictable)	Complex, Shared

The typology highlights the increasing degree of personalization and, correlatively, the intensification of risk for the user and the growing complexity of potential liability.

Algorithms and the Visibility of Legal Information: Digital Distribution and Legal Impact

The hybrid character of online legal advice is decisively amplified by the way platforms structure and distribute information. Legal content does not reach the user at random; rather, it is filtered through algorithmic mechanisms that take into account browsing history, the

aggregated behavior of other users, personal data, and technical parameters specific to each platform.

In this context, algorithms function as invisible intermediaries (Pasquale, 2015): although they do not, as a rule, “create” legal content, they determine its visibility and its appearance of relevance - establishing which answer appears first, which opinions are reinforced through repetition, and which content is signaled as “trustworthy.” As a result, incomplete or erroneous information may acquire an aura of authority, while accurate information may remain marginal.

The main legal consequence is that algorithms do not merely mediate content; they contribute to shaping user trust and, implicitly, to the configuration and redistribution of legal risk in the digital environment (Floridi, 2014; Busch & De Franceschi, 2021).

Digital Platforms as Informational Actors

In the context of online legal advice, the platform does not operate as a neutral infrastructure (Balkin, 2021), but as an informational actor that configures visibility, ranking, and the reception context of the message. The legal relevance follows from the fact that these design choices can generate reasonable expectations of authority and can transform questionable information into effective harm. Consequently, the platform must be treated distinctly in the liability analysis, alongside the author and the recommendation mechanisms (developed in Section 2).

The Asymmetry of Legal Protection for the Digital Consumer: Romania vs. Republic of Moldova

The transformations of online legal advice must be examined in light of the normative differences between Romania and the Republic of Moldova.

Romania applies the Digital Services Act (DSA) directly, operating within a European framework focused on prevention, transparency, and the mitigation of systemic risks generated by platforms. This model promotes a proactive vision of digital responsibility and of the protection of the vulnerable user.

The Republic of Moldova, although outside the DSA regime, has at its disposal a modern normative instrument - Article 2018 of the Civil Code - which governs liability for harm caused through legitimate reliance on erroneous information. This solution provides a solid conceptual basis for addressing digital risks, centered on informational asymmetry and on protecting the user who is situated in a position of cognitive inferiority.

Moldovan legal scholarship, notably through the works of Olesia Plotnic and Dorin Cimil, offers important reference points for understanding the imbalance between provider and recipient, unfair terms, and the formation of trust in the context of online information. Although formulated within a pre-algorithmic framework, these contributions support the conceptualization of informational liability within the logic of protecting the digital consumer.

Towards a Model of Segmented Liability in the Digital Environment

In light of the elements outlined above, the traditional author–recipient scheme becomes insufficient to explain the mechanisms through which harm is produced in the digital environment.

A conceptual framework is needed that distinguishes the roles and contributions of the actors involved. To this end, the paper proposes the model of segmented liability, in line with the literature on algorithmic regulation and normative personalization in digital ecosystems (Busch & De Franceschi, 2021).

The next section presents the framework established by the Digital Services Act and the way it reconfigures legal responsibility in the digital environment, assigning platforms an active role in managing the risks associated with the distribution of legal content.

The Digital Consumer: A Vulnerable Subject of Online Legal Advice

The vulnerability of the digital consumer stems from structural features of the digital informational ecosystem—information asymmetry, algorithmic opacity, and the ambiguous legal status of online-distributed content—which expose users to misinterpretation or unjustified reliance on answers that carry a professional appearance (Helberger et al., 2022).

Online legal advice is no longer addressed to an abstract user but to a digital consumer: a person interacting with legal information delivered in opaque technical environments, without clear benchmarks for professional validation and, often, without the capacity for critical evaluation. Under these conditions, harm may arise not only from erroneous content, but also from the mechanisms through which information is framed as credible and relevant.

This position of cognitive inferiority echoes the classical consumer who acts on trust rather than expertise. Yet, unlike traditional goods or services, the digital consumer confronts a trust-based (*credence*) service whose correctness cannot be autonomously verified before or after use. Accordingly, trust is not professionally built, but can be technologically induced through visibility, positioning, and algorithmic repetition (Sax, Helberger, & Bol, 2018).

Perceived relevance or authority does not necessarily track intrinsic quality; it may be produced by the platform via distribution and signaling mechanisms. This generates a climate of apparently legitimate, yet structurally fragile, trust that amplifies legal risks.

Within this framework, liability analysis must extend beyond the classical author–recipient relationship to reflect a multi-actor reality: not only the content author matters, but also the platform that shapes the informational context and the algorithmic mechanisms that may artificially consolidate credibility. The segmented liability model captures this distribution of responsibility without conflating roles.

Legal responsibility in the digital environment should therefore be understood not only as a post-factum remedy, but also as an instrument for protecting the consumer’s legitimate trust within an informational environment marked by systemic imbalances.

The Digital Services Act and the Reconfiguration of Digital Platforms’ Responsibility

The Digital Services Act (Regulation (EU) 2022/2065) marks a turning point in the legal regulation of digital platforms in the European Union. While the eCommerce Directive entrenched, for more than two decades, the paradigm of the passive intermediary and technological neutrality, the DSA introduces a different normative architecture in which platforms acquire duties of diligence connected to the way they organize, distribute, and amplify information.

In the context of online legal advice, the DSA is relevant because it introduces duties of diligence concerning the architecture of content distribution and reaction mechanisms, with a direct impact on informational risks and on user protection.

From Passive Intermediary” to „Responsible Actor”: The New DSA Paradigm

The model established by the eCommerce Directive was built on the premise that platforms exercise limited control over transmitted or stored content. The DSA reconfigures this paradigm through a structural shift: platforms acquire duties of diligence and legal responsibility for the informational architecture they administer, and technical decisions such

as moderation, recommendation, and ranking are treated as having legally relevant effects (Kuczerawy, 2021; Husovec, 2022).

Consequently, distribution and recommendation become legally relevant as part of the platform’s duties of diligence, rather than merely serving as the technical “backdrop” of content.

Platforms’ Obligations in the Context of Online Legal Advice

Recent scholarship (Douek, 2021; Van Hoboken & Ó Fathaigh, 2022; Schulz & Dankert, 2023; Peguera, 2023) emphasizes that the DSA introduces a set of obligations that directly affect how information is perceived and used online. In the case of online legal advice, these obligations are all the more salient insofar as errors may have concrete consequences for the exercise of rights.

In essence, platforms must ensure meaningful transparency regarding recommendation and ranking criteria, so that the user can distinguish between algorithmic visibility and professional validation; in parallel, notice-and-action mechanisms require proportionate reactions to content reported as harmful, and for very large platforms the obligations extend to the assessment and mitigation of systemic risks, including through audits and governance measures. Complementarily, the DSA strengthens user control over recommendations (including alternative/non-personalized options), limiting the effects of overexposure and “validation through repetition.” Although the DSA does not directly regulate AI, the use of automated tools in delivering or amplifying information may be treated as a risk factor within the logic of duties of control and prevention, particularly where content affects the exercise of rights (Frosio, 2021).

Romania and the Republic of Moldova in Relation to the DSA: A Comparative Regulatory Overview

Regulatory differences that matter for online legal advice become more visible through a comparison between Romania (an EU Member State, with the DSA directly applicable), the Republic of Moldova (outside the DSA regime), and the EU framework as the normative matrix. In Romania, the DSA and national implementation mechanisms shape a framework oriented toward prevention and accountability, with obligations concerning transparency, risk management, and compliance oversight. In the Republic of Moldova, in the absence of a DSA-equivalent framework, the analysis remains anchored predominantly in civil law (especially Article 2018 of the Civil Code), emphasizing ex post compensation for harm and lacking specific instruments of algorithmic governance.

To illustrate these differences comparatively, Table 2 provides a synthesis of the regime applicable to online legal advice in the two states and at EU level, from the perspective of platform responsibility, user protection, and the treatment of algorithmic risks.

Table 2. Comparative Table: Legal Frameworks Governing Online Legal Advice

Regulatory Element	Romania (DSA + Law 50/2024)	Republic of Moldova	EU / DSA Framework
Applicable legal framework	Direct DSA application; Law 50/2024 operationalizes it; ANCOM designated as supervisory authority; layered governance combining DSA with civil law	No specific digital regulation; relies on general civil liability under Article 2018	Comprehensive DSA framework; coordinated oversight; shared standards.
Platform liability	Due diligence, notice-and-action, risk assessment, audits; liability also under national civil law	No specific platform duties; liability assessed through classical tort law	Multi-level obligations: moderation, risk audits, algorithmic accountability.
Transparency and information	Mandatory algorithmic transparency, explanations for automated decisions, option for non-personalized content display	No regulation on transparency or algorithmic logic	„Meaningful transparency” concept: clarity on algorithmic processes.
User protection	Strong procedural and preventive protections via DSA; supplemented by traditional remedies under civil law	Civil protections via interpretation of various laws; lacks digital-specific procedural tools.	Comprehensive procedural rights and risk-prevention mechanisms
Algorithmic governance	Explicit obligations: algorithmic risk audits, mitigation, non-personalized options	No recognition of algorithmic risks in legislation	Central to DSA: periodic audits, prohibition of manipulative algorithms for VLOPs
Online legal advice	Treated as high-risk content; platforms must manage visibility and categorization responsibly	Viewed as general information; protection depends on Article 2018 and fault analysis	Framed as systemic risk content with potential rights implications
AI-generated content	Indirectly regulated via technological risk obligations and transparency	Entirely unregulated from a digital perspective	Treated as high-risk content; special oversight for VLOPs

The table highlights the functional asymmetry between the two systems: in Romania, the emphasis falls on ex ante obligations (transparency, diligence, risk assessment), whereas in the Republic of Moldova protection is achieved predominantly ex post, through civil-law instruments. In this context, it becomes necessary to articulate a conceptual framework capable of integrating civil law with platform governance and the role of algorithms in shaping legal risk.

Conceptual Implications and the Shift Toward a Segmented Liability Model

The DSA shifts the focus from the isolated speaker to the distribution infrastructure, recognizing the role of digital architecture in generating risk. Against this background, an analytical instrument for the differentiated allocation of responsibility becomes useful.

The next section develops the segmented liability model and its operational utility.

The Segmented Liability Model: A Legal Architecture Centered on the Digital Consumer

Within platformized ecosystems, online legal advice generates legal risk that cannot be reduced to the author–user dyad.

Harm typically takes shape through a combination of factors: the content provided; the manner in which it is presented and distributed within the platform; and the amplifying effects of algorithmic mechanisms on the visibility and perceived credibility of information—vis-à-vis a consumer situated in a position of cognitive vulnerability and not reasonably able to autonomously verify the accuracy of the response (a *credence service*).

Against this background, the paper proposes the segmented liability model as an analytical tool for the differentiated allocation of responsibility within a multi-actor informational chain, compatible both with the European regulation of platforms and with the logic of civil liability in the legal systems under analysis (Busch & De Franceschi, 2021; Floridi, 2014).

The illustrative anchoring of these distinctions through jurisprudential reference points and factual incidents is developed subsequently in Section 5.

The Foundation of the Model: The Interaction Between Author, Platform, and Algorithm

The factual and conceptual premises concerning the platformized distribution of legal information and the role of recommendation mechanisms were established in Section 1.

Accordingly, liability analysis can no longer remain confined to the author–user axis, because harm is often formed through the interaction between the legal content provided, the delivery architecture, and the credibility signals produced by the platform, as well as the opaque amplification/validation through recommendation and ranking (Husovec, 2022; Kuczerawy, 2021; Douek, 2021).

The segmented liability model therefore proposes an analytical separation of these causal contributions, in order to identify the pertinent actor and the legally significant conduct within technological causal chains, avoiding both automatic mono-causal attribution and the dilution of responsibility through the conflation of roles.

The Three Tiers of Liability in the Segmented Model

The segmented liability model operates with three analytical tiers, corresponding to distinct causal contributions in the formation of legal risk and legal harm. The delimitation seeks to separate elements of content, informational architecture, and algorithmic amplification, so that the attribution of responsibility can be assessed in a differentiated manner.

The Operational Structure of the Segmented Model

In digital environments, attributing liability to a single actor is often inappropriate, since harm frequently results from the interdependence between content, informational architecture, and algorithmic amplification.

Operationally, the model separates the relevant causal contributions and correlates them with the forms of liability applicable under Romanian law, Moldovan law, and within the EU framework.

Table 3 synthesizes, for each tier, its role in generating risk, the typologies of contribution to harm, and the potentially applicable liability regimes.

Table 3. The Structure of Segmented Liability in Online Legal Advice

Actor	Role in Risk Generation	Contribution to Harm	Potential Form of Liability
Author of legal content	Produces the initial legal information; determines accuracy, clarity, and completeness	Direct legal error; omission of essential information; ambiguous legal formulations; creation of unjustified trust	Civil liability (tort or contract-based, depending on whether a contractual relationship exists)
Platform	Creates and manages the informational architecture; ranks, promotes, and contextualizes content	Amplification of erroneous content; lack of algorithmic transparency; inadequate response to notices; creation of unwarranted professional authority	Independent civil liability; technological and procedural obligations under the DSA (risk assessment, audits, etc.)
Algorithm	Selects, ranks, and prioritizes legal information	Distortion of accurate information; unintentional amplification of incorrect content; false validation through placement; excessive homogenization of information flows	Not a legal subject per se; indirect liability through the platform, based on obligations for audit, control, and transparency

On the basis of this structure, the following section highlights the model’s analytical advantages.

The Analytical Advantages of the Segmented Liability Model

The segmented liability model has three main advantages.

First, it enables a differentiated identification of the source of legal harm in the digital environment, avoiding the reduction of the phenomenon to a “single author” and delineating the relevant contributions of the author, the platform, and algorithmic mechanisms.

Second, it coherently integrates civil-liability principles with the preventive layer of digital governance: it does not replace traditional rules, but renders them operational within a framework in which, in Romania, DSA obligations (transparency, procedures, risk assessment) operate complementarily to civil remedies.

Third, it treats algorithmic risks as autonomous vectors of amplification, which is useful for explaining situations where harm does not derive from an isolated error, but from effects of ranking, repetition, and technical validation.

Through this structure, the model also provides a conceptual basis for discussing generative AI, where the boundaries between author, platform, and technical instrument tend to blur.

The next section develops the model’s comparative application in Romania and the Republic of Moldova, while Section 5 anchors it illustratively in jurisprudential reference points and factual incidents in order to clarify diligence expectations at each tier.

The Application of the Segmented Liability Model in Romania and the Republic of Moldova

The comparative analysis of how the segmented liability model operates in Romania and the Republic of Moldova highlights two distinct ways of integrating the technological dimension into the assessment of legal risk associated with online legal advice.

The difference is not exclusively legislative; it also concerns how mechanisms of prevention, proof, and redress function within a multi-actor digital ecosystem.

Against this background, the section aims to delineate the contribution of each tier and to highlight their implications for the protection of the digital consumer.

Romania – The Effective Functioning of Segmented Liability within an Integrated Regulatory Framework

In Romania, the application of the DSA, read together with Law no. 50/2024, renders segmented analysis operational by introducing an ex ante layer of obligations concerning transparency, reaction procedures, and risk management, which operates complementarily to civil-law remedies. From the civil-law perspective, the author remains the natural target of liability for the accuracy and completeness of content; from the perspective of the platform’s own conduct, design and governance choices become relevant insofar as they shape users’ reasonable expectations and the conditions of distribution/amplification.

Within this configuration, algorithmic mechanisms are not treated as subjects of law, but as objects of the operator’s organizational control (auditability, traceability, functional safeguards). By reducing informational asymmetries (particularly through transparency duties and procedural obligations), the Romanian framework increases the prospects of differentiated causal attribution and reduces the tendency for the dispute to “collapse” exclusively onto the most visible actor.

The Republic of Moldova – Doctrinal Application of the Model within Civil Law

The Republic of Moldova does not currently have a digital framework equivalent to the Digital Services Act. Nonetheless, a systematic analysis of domestic legislation reveals a normative core that can support—through evolutionary interpretation—the application of the segmented liability model.

Article 2018 of the Civil Code provides a foundation for liability based on legitimate reliance on incorrect information or recommendations, while rules on advice and tort liability allow liability to be engaged even in the absence of a formal contractual relationship. Related legislation on e-commerce, personal data protection, and access to information complements this framework, offering anchoring points for analysing platform responsibility and algorithmic personalization; however, the role of the platform and of algorithmic mechanisms is not yet structured through explicit duties of transparency, audit, or preventive risk management.

Applying the segmented model in the Republic of Moldova is therefore possible, but it remains conditioned on extensive doctrinal interpretation and on leveraging existing civil-law institutions, particularly liability grounded in legitimate trust. Functional differences vis-à-vis Romania are comparatively synthesized in Section 4.3 and analysed in Section 4.4.

Comparative Synthesis of the Segmented Liability Model in Romania and the Republic of Moldova

Table 4 synthesizes how the segmented liability model is reflected in each legal order, from the perspective of regulation, the structure of responsibility, and user protection

Table 4 – Application of the Segmented Liability Model in Romania and the Republic of Moldova

Criterion	Romania	Republic of Moldova
Primary regulation	Harmonized digital European framework: DSA directly applicable, supplemented by Law No. 50/2024 as the national mechanism for implementation and oversight, in correlation with the general tort liability rules in the Civil Code.	Classical civil law framework: Civil Code (Art. 2018, Art. 1415–1418, Art. 1979–1982) and related laws (Law No. 284/2004 on e-commerce, Law No. 133/2011 on personal data, Law No. 241/2007 on electronic communications, Law No. 148/2023 on access to information).
Structure of liability	Distributed across distinct layers: author – platform – algorithm, under a cumulative regime combining traditional civil liability with preventive digital obligations.	Predominantly linear: author – user; the author remains the central pivot of liability.
Platform responsibility	Expressly regulated through the DSA: obligations of transparency, algorithmic auditing, risk management, and notice-and-action mechanisms, without excluding civil liability for own actions.	Not specifically regulated; liability possible only through extensive doctrinal interpretation, relying on the theory of legitimate reliance.
Role of algorithms	Recognized as legal risk vectors; subject to evaluation, audit, and control obligations as part of platform responsibility.	Absent as an autonomous legal concept; may be conceptually integrated through interpretation of Article 2018 of the Civil Code.
User protection	Strengthened protection: procedural and preventive mechanisms established under the DSA, supplemented by classical civil remedies (tort liability).	Predominantly post-factum protection; user bears the burden of proving the harm.
Liability for amplification of error	Directly regulable through platform obligations concerning information architecture and algorithmic amplification.	Difficult to prove in practice; lacks technological instruments for prevention.
Compatibility with segmented model	High – the model integrates naturally into a layered normative framework (civil + digital).	Medium – dependent on doctrinal developments and potential legislative reforms.
Level of digital maturity	Advanced – functionally integrated within the EU’s digital regulatory architecture.	Emerging – requires adaptation of civil law norms to digital realities.
Evolutionary direction	Consolidation of the existing framework and expansion toward legal AI regulation.	Digital reform and gradual convergence with European standards.

The synthesis highlights differences that are not only normative but also functional: in Romania, there is a framework that facilitates integrating the technological dimension into risk analysis, whereas in the Republic of Moldova civil-law instruments of subsequent compensation predominantly prevail.

The Preventive–Reactive Gap and Convergence Scenarios

Based on the analysis in Sections 4.1–4.3, the central difference between the two systems may be described as a preventive–reactive gap: in Romania, the DSA-related ex ante layer internalizes risks linked to distribution and recommendation, while in the Republic of Moldova ex post civil-law instruments predominate, with a heavier evidentiary burden on the user.

In the Republic of Moldova, conceptual convergence is possible along three complementary tiers. A first tier is doctrinal, by leveraging existing civil-law institutions—fault, advice, and legitimate trust—to extend the analysis beyond content as such toward the infrastructure that confers visibility and authority on information in the digital environment. A second tier is normative and gradual, which could introduce minimal transparency duties and functional notice-and-action procedures for potentially harmful content, without fully replicating the DSA apparatus. A third tier concerns evidentiary convergence and risk governance, by clarifying diligence standards and establishing mechanisms for access to relevant information (for example, recommendation criteria, logs, traceability), so that liability attribution becomes operational within technological causal chains. Overall, the differences between the two systems primarily reflect Romania’s membership in the Union framework and the existence of an *ex ante* layer of digital governance, whereas the Republic of Moldova remains a space for civil-law adaptation with potential for gradual evolution.

Illustrative Validation of the Segmented Liability Model: Jurisprudential Reference Points, Factual Vignettes, and the Sustainability of Digital Governance

The Role of Illustrative Validation and Selection Criteria

In order for the segmented liability model to be usable beyond the purely conceptual level, this section selectively draws on a small number of publicly visible jurisprudential reference points and factual vignettes. They are not treated as generalizable empirical “evidence” and do not aim to provide a quantitative mapping of litigation; rather, they function as plausibility tests. They help identify the legally relevant conduct, the pertinent actor, and the way in which an informational risk can translate into harm in digital contexts.

The selection of examples follows three benchmarks: first, the possibility of associating each example predominantly with one of the model’s tiers (author–platform–algorithmic mechanism), without artificially conflating roles; second, the clarity of the causal chain, from the production or uptake of information to the harmful consequence; third, their relevance for outlining the expected conduct at each tier (diligence and verification; design and warning; control, audit, and traceability).

Intentionally, these reference points are treated as analytical units: they allow a legal “cut-out” of the pertinent conduct in *credence service* situations, where autonomous verification of informational accuracy is, realistically, impracticable.

The “Author” Tier: the Standard of Diligence and the Duty to Verify When Using Generative Tools

At the author tier, legal risk arises at the level of the conduct of the person who produces, selects, or reuses legal information and presents it as a basis for a decision. The use of a generative tool does not “transfer” responsibility; it changes the diligence context: it increases the importance of source verification, final control over assertions, and filtering of plausible errors precisely because of their persuasive form.

A useful reference point, even if it does not concern online legal advice *stricto sensu*, is *Mata v. Avianca* (S.D.N.Y., 2023), which became emblematic for the risk of fictitious citations generated by generative tools and then introduced into professional circulation without verification.

The analytical stake, for the model, is a clear delimitation of the relevant conduct: not the technical “hallucination” as such, but the author’s conduct in validating and transmitting as

true content that could have been verified by reasonable means, thereby increasing the likelihood of harm (material, professional, or procedural).

Operationally, the author tier activates classic criteria (fault/diligence, foreseeability, causation), but within a framework in which the message’s “technologically credible” form may induce disproportionate reliance. This explains why the duty to verify becomes the pivotal criterion at this tier.

The “Platform” Tier: the Architecture of Trust and Responsibility for the Delivery Interface

At platform level, the focus is not on content *per se*, but on how content is delivered as a “service”: the official interface, credibility signals, functional warnings, and the capacity to correct problematic information once it appears. At this tier, the typical risk is misleading the user through “contextualization” (how the message is presented and what reasonable expectations it generates).

Moffatt v. Air Canada (B.C. Civil Resolution Tribunal, 2024) is useful precisely because it treats information provided through a chatbot as part of the service communication, and the entity operating the tool cannot dissociate itself from its own official channel by arguing that the user “should have verified elsewhere.”

For the segmented model, the case is relevant because it delineates the platform tier: choosing to provide information through an official conversational interface triggers requirements of accuracy, warning, and corrective remedies, independently of the automated character of generation.

The “Algorithm” Tier: Opaque Amplification, Design Defects, and Risk Governance

At the tier of algorithmic mechanisms, the risk is no longer a punctual error, but a systemic effect: selection, ordering, and personalization can produce false validation (through positioning/repetition), overexposure, and persistence, while opacity impedes both user self-correction and causal attribution in litigation. Since the algorithm is not a subject of law, legal analysis shifts toward the governance duties of the actor who operates it: control, monitoring, functional safeguards, auditability, and traceability.

The episode of the “Tessa” chatbot, launched by the National Eating Disorders Association, is relevant as a risk-governance vignette: a conversational tool presented with the appearance of specialized support was withdrawn in 2023 following public reactions concerning responses considered inappropriate for the target audience. This highlights the importance of *safety-by-design* guarantees (delimitations, functional warnings, escalation to human support, monitoring, and rapid intervention).

Finally, the litigation *Garcia v. Character Technologies Inc.* (M.D. Fla., 2024, pending) is useful as a “test” for the register of design defects and foreseeable risks of conversational interaction (anthropomorphization, engagement strategies, emotional validation).

Even as a pending case, it is methodologically relevant: it shifts the discussion from an isolated exchange (“what was said”) to the control framework (“what limits, monitoring, and intervention mechanisms were instituted”)—precisely the zone in which the algorithmic tier becomes legally intelligible through the operator’s obligations.

In model terms, the stake of the algorithmic tier is not the identification of an “author” of the error, but the delimitation of foreseeable risk generated by design and operation, and of the control obligations incumbent on the platform in relation to amplification effects, opaque validation, and repeated exposure.

Implications for the Model: Confirmations, Tensions, and Limits of Segmentation

Taken together, the examples discussed support a central intuition of the paper: in digital ecosystems, harm associated with online legal advice is generally not mono-causal. It arises from a combination of contributions: error, omission, or ambiguity at the level of content (author); the conversion of that content into harm through the trust-and-delivery context created by the platform interface (platform); and opaque amplification or validation through recommendation mechanisms and conversational design (algorithm, as an object of platform governance). Accordingly, a strictly author–user analysis risks overlooking what, in platformized environments, often makes the difference between questionable information and effective harm: the infrastructure that confers visibility, authority, and persistence on content.

Practically, this explains the value of the segmented liability model as an orienting grid. The tiered distinction remains productive because it separates roles without conflating them, helping identify the pertinent defendant and the legally significant conduct within a technological causal chain—without forcing a “single culprit” narrative or diluting the distinct contributions of the author, the platform, and algorithmic-risk governance.

The tensions, however, remain structural. Segmentation is difficult to operationalize without access to recommendation criteria, logs, and traceability, and these evidentiary constraints tend to re-concentrate litigation on the “visible” actor (the author), even where distribution mechanisms made a material contribution. This is where an *ex ante* governance layer (where it exists) shows its value: it does not replace civil remedies, but it can reduce the informational asymmetries that hinder liability attribution in technological causal chains.

In ECO4ALL terms, the stake is to avoid externalizing technological risks onto consumers and to shape sustainable digital markets through accountability and risk governance. The reference points analyzed indicate the need to treat recommendation systems and conversational design as objects of the platform’s organizational diligence: proportionate risk assessment and mitigation, meaningful transparency, effective control and audit mechanisms, and operational procedures for intervention and correction.

Finally, this section should be read in an illustrative key: the examples neither ground generalizations nor substitute an empirical litigation analysis; they provide controlled reference points showing how the model applies when risk is generated through the interaction between content, interface, and recommendation mechanisms.

SDG12 and the Circular Economy of Legal Information: From Informational Risk to Sustainable Governance

In the digital economy, legal information circulates in a quasi-circular regime: it is produced, taken up, repackaged, recommended, and recirculated at scale, while its utility for users is decisively shaped by distribution architectures and the credibility signals attached to content. Absent minimal guarantees of traceability and control, the same error can be replicated and amplified into a systemic externality: the costs of being misled fall predominantly on the vulnerable consumer, while the economic benefits of content circulation and attention monetization accrue to the platformized infrastructure. In this sense, SDG12 (Responsible Consumption and Production), as a goal of the UN 2030 Agenda, can be translated juridically into a requirement of responsible production and distribution of legal information online, including by limiting the persistence and recirculation of erroneous or misleading content.

The segmented liability model provides an operational bridge between fairness, accountability, and sustainability. Fairness follows from reducing structural asymmetries: the model separates causal contributions and explains why the consumer, situated in a *credence*

service, cannot be treated as the final validator of accuracy. Accountability results from the differentiated allocation of obligations: the author bears responsibility for diligent verification of content; the platform for the delivery architecture and the trust signals it produces; and algorithmic risk is treated as an object of platform governance (control, audit, traceability). Sustainability is understood as internalizing risks in design and operation so that errors are not scaled and recirculated as informational externalities; where an *ex ante* layer exists (such as the DSA), this logic is reinforced through meaningful transparency, functional corrective procedures, and risk-management mechanisms capable of reducing the social costs of digital harm and preventing their externalization onto consumers.

Conclusions, Limitations, and Future Directions: Legal Responsibility in Online Legal Advice and the Protection of the Digital Consumer

Conclusions

The paper began by asking whether classical civil-liability models, centered on the author–user relationship, can adequately explain harm produced in online legal advice. The analysis confirms the working hypothesis: in multi-actor digital ecosystems, harm typically results not only from the content provided, but from the interaction between content, delivery architecture, and distribution and recommendation mechanisms. In this framework, online legal advice often functions as a *credence service*, and the digital consumer cannot realistically be treated as the final validator of accuracy.

On this basis, the study’s central contribution is the formulation and operationalization of the segmented liability model (author–platform–algorithmic mechanism). The model provides an analytical tool for legally “carving out” relevant conduct and for avoiding both mono-causal simplification (automatic attribution of harm to the author) and the dilution of responsibility through conflated roles. Practically, segmentation operates as an orienting grid, enabling the identification of the pertinent actor and legally significant conduct within a technological causal chain, without reducing the phenomenon to a “single culprit.”

The comparative analysis reveals a relevant functional difference between Romania and the Republic of Moldova. Romania operates within a layered framework in which civil-law remedies are complemented by an *ex ante* layer of digital governance under the DSA (and domestic implementation mechanisms), rendering the platform’s contribution and algorithmic risk more legally intelligible through transparency, risk assessments, procedures, and notice responses. The Republic of Moldova, lacking a functional DSA equivalent, remains predominantly *ex post*, but it retains relevant civil-law anchors—especially legitimate trust (Article 2018 of the Civil Code)—which can, through evolutionary interpretation, extend analysis beyond content to delivery and validation infrastructure.

The illustrative validation section (jurisprudential reference points and factual vignettes) reinforces the model’s methodological plausibility: the author tier foregrounds diligence and the duty to verify, including when generative tools are used; the platform tier shows how interfaces and credibility signals can convert problematic information into effective harm; and the algorithmic tier clarifies why risk becomes legally intelligible through operator governance (control, audit, traceability, and functional “brakes”), rather than by attributing legal subjectivity to the algorithm.

Finally, integrating the SDG12 perspective and the “quasi-circular economy” of legal information completes the argument coherently: absent traceability and control, errors are recirculated and amplified, and costs are externalized onto the vulnerable consumer. The segmented model supports a fairer allocation of risk by reducing structural asymmetries

(fairness), differentiating duties (accountability), and internalizing risks in design and operation (sustainability), with stronger potential where an ex ante governance layer exists.

Practical and Normative Implications

The analysis yields three main implications for the civil-law characterization of harm produced through online legal advice.

At the author tier, the diligence standard remains the anchor of liability, but it must be calibrated to the risks of “technologically credible” content. The duty to verify becomes decisive, alongside avoiding the presentation of unverified content as certain and explicitly delimiting the level of personalization (general guidance versus a recommendation applied to a concrete situation).

At the platform tier, responsibility becomes legally relevant whenever the platform constructs a context of trust: delivering information through an official interface, attaching signals of authority, omitting functional warnings, or responding inadequately to content with harmful potential. Relevance does not turn on automated generation, but on how the platform shapes users’ reasonable expectations and the conditions under which they rely on information.

At the level of algorithmic risk governance, expected operator conduct includes meaningful transparency on recommendation criteria, auditability, traceability (relevant logs), intervention and correction mechanisms, and functional limits in sensitive contexts. Without these safeguards, causal attribution becomes difficult in litigation, and disputes tend to re-concentrate on the “visible” actor (the author), even when distribution or amplification materially contributed to the harm.

Limitations

The paper acknowledges several limitations that flow directly from its methodological choices.

The inquiry is predominantly normative and doctrinal. It does not seek empirical validation of litigation frequency, nor a quantitative measurement of how online legal advice affects user behavior or legal decisions adopted on its basis.

The jurisprudential reference points and factual vignettes serve an illustrative function, as plausibility tests for the causal chain and for delineating tiers (author–platform–algorithm). They are not a representative sample and cannot support statistical generalizations.

The Romania–Republic of Moldova comparison is deliberately focused on mechanisms for attributing liability and on conceptualizing the contribution of platforms and algorithmic distribution. It is not an assessment of enforcement effectiveness, institutional capacity, or a systematic mapping of domestic judicial practice.

The analysis remains centered on civil liability and consumer protection, without exhaustively addressing intersections with professional/disciplinary liability, criminal liability, or the full range of public-law sanctioning mechanisms.

Finally, the rapid evolution of AI tools and platformized architectures may quickly change technical risk profiles and design practices. Accordingly, the model’s concrete applications realistically require periodic updates, even if the conceptual structure remains useful as an analytical grid.

Future Research Directions

Based on the findings and limitations, several avenues for further research emerge.

Empirically, it becomes relevant to validate the model by mapping litigation—and the phenomenon of “non-litigation”—in online legal advice, including an analysis of barriers to

access to justice and of the difficulties in identifying the pertinent actor and characterizing technological causal chains.

From an evidentiary and access-to-information perspective, it is necessary to develop a traceability framework (relevant logs, recommendation criteria, auditability) and to assess legal instruments capable of reducing informational asymmetries in disputes involving algorithmic distribution, amplification, and validation.

At the level of normative intersections, the model could be more explicitly integrated with developments in AI regulation and governance (transparency duties, technical and organizational standards) and with the modernization of liability regimes for digital products, to clarify complementarities and potential tensions between frameworks (De Bruyne, Dheu & Ducuing, 2023; Hacker, 2023).

Applicatively, the model merits testing across distinct platform types (service marketplaces, social networks, search engines, conversational applications) and content forms (from FAQs to contextualized or automated recommendations), with a view to refining tier-specific diligence standards and more precisely delineating risk thresholds.

For the Republic of Moldova, a practically significant direction is doctrinal and legislative-policy analysis of the gradual introduction of minimal functional mechanisms (basic transparency, notice-and-action, access to relevant data), compatible with the civil-law matrix and existing instruments, without presupposing full transplantation of the DSA apparatus.

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SUSTAINABLE BIOSURFACTANT PRODUCTION FROM INDUSTRIAL WASTE USING *PSEUDOMONAS PUTIDA* ICCF 391: A CIRCULAR ECONOMY AND CONSUMER PROTECTION PERSPECTIVE

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Abstract

The transition toward circular and sustainable production systems has increased the need for biodegradable, non-toxic, and environmentally friendly compounds that can serve as alternatives to conventional synthetic chemicals. Microbial biosurfactants are a promising class of bio-based molecules that can facilitate this shift, particularly when produced using agro-food waste as a substrate.

*In this study, the biosurfactant produced by *Pseudomonas putida* ICCF 391 was synthesized using a cost-effective mixed substrate consisting of glycerol (3%) and waste cooking oil (2%), effectively incorporating waste valorization into the bioprocess. Its physico-chemical stability was assessed over a broad range of temperatures (30-115 °C) and pH values (2-12), while its antimicrobial activity was evaluated against *Pseudomonas aeruginosa* ATCC 9027. The biosurfactant exhibited thermal and pH stability, and demonstrated antibacterial activity, producing a 29 mm inhibition zone.*

Beyond its functional properties, the study frames the biosurfactant within the framework of the circular economy, highlighting its potential to reduce waste, promote sustainable industrial practices, and enhance consumer protection through safer, biodegradable, and renewable alternatives to chemical surfactants. These findings support integrating biosurfactants into sustainable industrial systems and highlight their relevance to EU policy objectives on waste reduction, chemical safety, and consumer protection.

Key words: *microbial surfactant, *Pseudomonas* strain, industrial waste, circular economy.*

Introduction

The transition toward a circular economy has emphasized the need to minimize waste, extend product lifecycles, and develop environmentally friendly alternatives to conventional chemicals. Within the European Union, these objectives are embedded in strategic frameworks such as the Circular Economy Action Plan (CEAP, 2020), which promotes waste valorization, the use of renewable resources, and the development of safer chemical products with reduced environmental impact (Gaur et al., 2022; Qamar & Pacifico, 2023). In this context, microbial biosurfactants have emerged as relevant bio-based compounds due to their functional versatility and compatibility with sustainability and consumer safety goals.

Biosurfactants are amphiphilic molecules synthesized by a wide range of microorganisms, including species belonging to the genera *Pseudomonas*, *Bacillus*, *Candida*, and *Rhodococcus*. In comparison with conventional synthetic surfactants, microbial biosurfactants generally exhibit enhanced biodegradability, reduced toxicity, and stability under a broad range of environmental conditions (Deshmukh & Kathwate, 2023). These characteristics support their applicability in diverse industrial sectors such as detergents, cosmetics, pharmaceuticals, agriculture, environmental remediation, and food-related processes (Mohanty et al., 2021).

The use of agro-industrial residues as substrates for biosurfactant production represents a key strategy within the circular bioeconomy, enabling the transformation of low-value waste into high-value functional products. Substrates such as waste cooking oil, whey, and crude glycerol are abundant, low-cost, and environmentally challenging materials that can be effectively valorized as feedstocks for microbial biosurfactant production (Praveesh et al., 2011; Soares da Silva et al., 2017). Their utilization into bioprocesses not only contributes to waste reduction, but also improves the economic feasibility and sustainability of biosurfactant production.

Therefore, in this study, the biosurfactant produced by *Pseudomonas putida* ICCF 391 using a low-cost mixed substrate composed of glycerol and waste cooking oil was evaluated in terms of its physico-chemical stability and antibacterial activity. In addition to assessing its functional properties, the work situates the production process within a circular economy framework, emphasizing its relevance for sustainable industrial applications and the development of safer, bio-based alternatives to synthetic surfactants.

Materials and methods

Biologic material

Pseudomonas putida ICCF 391 strain used in this study belongs to Collection of Microorganisms of Industrial Importance (CMII-ICCF-WFCC 232).

Culture medium and cultivation conditions

The strain was maintained on M44 agar slant, with the following composition (g/v): glycerol 5.0%, yeast extract 1.0%, bacto-peptone 1.0%, agar 2.0%. The culture medium was prepared with distilled water, adjusted to a pH of 6.5-7.0, and sterilized for 15 minutes at 121°C. The pre-inoculum consisted of bacterial strains incubated at 30°C for 48-72 hours, on M44 agar plates. The inoculum and biosynthesis media used for biosurfactant production contained % (v/v): glycerol 3.0, waste cooking oil 2.0, as carbon sources, 1.0 yeast extract, and 1.0 bacto-peptone as nitrogen sources. Also in this case, the culture media were prepared with distilled water, adjusted to a pH of 6.5-7.0, and sterilized at 121°C, for 15 minutes. For the submerged

fermentation, Erlenmeyer flasks of 500 mL capacity, with 100 mL medium, were used. Bioprocess conditions were performed at 30°C for 72 h on a rotary shaker at 220 rpm.

Stability and antibacterial activity of biosurfactant

In order to evaluate the production of biosurfactant by *Pseudomonas putida* ICCF 391, submerged bioprocesses in 500 mL flasks with 100 mL medium on a rotary shaker at 220 rpm were performed. Then, the procedure used by Foukia et al. (2016) to test the stability of the biosurfactant was followed.

To investigate the stability of biosurfactants at different temperature values, the supernatant obtained after centrifugation of the biosynthesis medium (9000 rpm for 20 minutes, 4°C), was kept at a constant temperature (30°C, 37°C, 50°C, 75°C, and 115°C) for 30 minutes, and then the emulsification index was determined. Similarly, the effect of pH was evaluated by adjusting the pH of the supernatant in the range of 2.0-12.0 using 2N HCl and 1N NaOH, and determining the emulsification index ($E_{24\%}$) (Alyousif et al., 2020).

In this case, 4 mL of supernatant was mixed with 6 mL of heptane, octane, and sunflower oil in separate tubes. Then, tubes were mixed vigorously for 2-5 minutes and kept for 24 hours (Pathak & Keharia, 2014). The emulsification index was determined by using the following formula:

$$E_{24\%} = (\text{height of the emulsified layer} / \text{total height of the liquid column}) \times 100$$

The experiments were performed in triplicate.

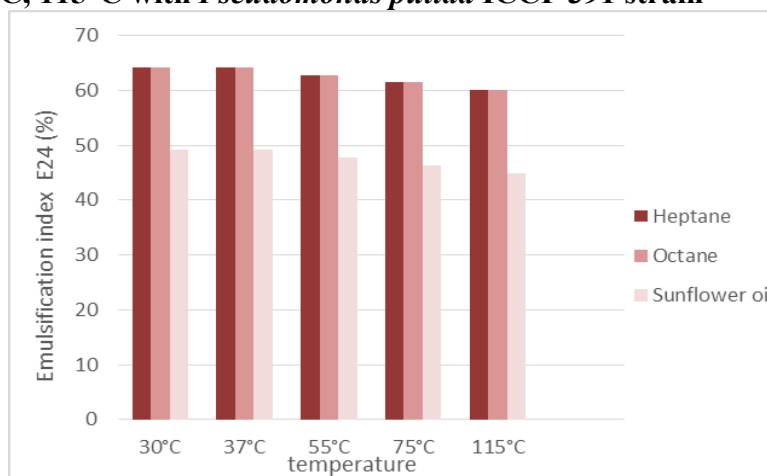
Regarding the evaluation of the antimicrobial activity, the biosurfactant produced by *Pseudomonas putida* ICCF 391 was isolated after 72 h of submerged fermentation through centrifugation, acid precipitation (pH 2.0, 2 N HCl, 4°C), and extraction with ethyl acetate. The organic phase was concentrated under reduced pressure to obtain a partially purified biosurfactant.

Its antibacterial activity was assessed against *Pseudomonas aeruginosa* ATCC 9027 using the agar diffusion (cylinder-plate) method adapted from Niamah, 2014. M44 agar medium was inoculated with a *Pseudomonas aeruginosa* ATCC 9027 suspension (10^8 CFU/mL), and 15 mL of the medium was poured into Petri plates and allowed to solidify. Two sterile stainless steel cylinders were placed at approximately 20 mm from the plate center, and 200 μ L of the partially purified biosurfactant was added to each cylinder. Plates were incubated at 30-35 °C for 18-24 h, and inhibition zones were measured. Experiments were conducted in triplicate, and results are reported as the mean of three independent assays.

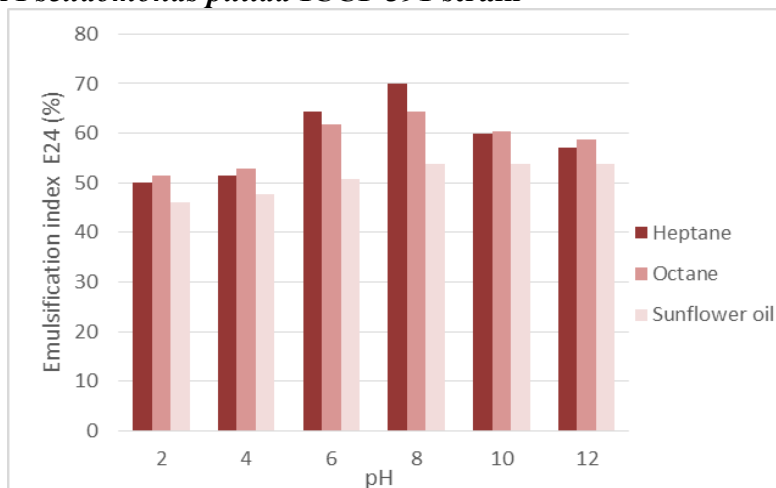
Results

Following 72 hours of submerged fermentation using a low-cost substrate composed of glycerol and waste cooking oil, the supernatant exhibited clear emulsification activity, indicating that the microorganism successfully utilized the mixed carbon sources to produce surface-active biocompounds. The results highlight that the biosurfactant produced by *Pseudomonas putida* ICCF 391 possesses physico-chemical and biological characteristics that support its application in sustainable and circular industrial systems.

As shown in Fig. 1, the $E_{24\%}$ results indicate that the biosurfactant maintains emulsification stability across a broad temperature range for heptane, octane, and sunflower oil. Even at higher temperatures, the emulsions remain stable, highlighting the thermal tolerance of the biosurfactant. The thermal stability broadens the potential applications of the biosurfactant, particularly in industrial processes subjected to demanding operating conditions.

Figure 1. Emulsification index for heptane, octane, and sunflower oil obtained at 30°C, 37°C, 55°C, 75°C, 115°C with *Pseudomonas putida* ICCF 391 strain

Also, the evaluation of pH tolerance provided similarly favorable results. The highest $E_{24\%}$ values were observed around neutral to slightly alkaline conditions (pH 6-8). Stability decreased slightly at acidic pH values below 6, while still maintaining good emulsification for heptane, octane, and sunflower oil. At strongly alkaline pH, $E_{24\%}$ values were lower than in the optimal range, but remained higher than those measured under strongly acidic conditions (Figure 2). Such broad pH tolerance confirms its versatility for industrial applications requiring stability under chemically demanding conditions, such as cleaning formulations, environmental remediation, and variable-pH processing environments.

Figure 2. Emulsification index for heptane, octane and sunflower oil obtained at pH 2, 4, 6, 8, 10, 12 with *Pseudomonas putida* ICCF 391 strain

Regarding the antimicrobial activity of the partially purified biosurfactant, obtained after post-biosynthesis processing, it was analyzed against the microbial strain *Pseudomonas aeruginosa* ATCC 9027. As we can see in Figure 3, biosurfactant showed antimicrobial activity against the test bacterial strain, indicated by an inhibition zone of 29 mm. This bioactivity enhances the biosurfactant's potential applicability in the formulation of natural disinfectants, preservative systems, cosmetic products with antimicrobial attributes, and food industry sanitation technologies. The dual functionality-surfactant behavior combined with antimicrobial activity-further strengthens its commercial and environmental value.

Figure 3. Antibacterial activity of biosurfactant against *Pseudomonas aeruginosa* ATCC 9027 strain



Therefore, the results are consistent with recent studies demonstrating that biosurfactants maintain stability at elevated temperatures and across a broad pH range (2-12) (Adebajo et al., 2019).

Additionally, the biosurfactant produced by *Pseudomonas putida* ICCF 391 exhibited antibacterial activity against *Pseudomonas aeruginosa*, indicating its potential application as an antimicrobial agent in pharmaceutical, food, and related industries. These functional properties highlight the biosurfactant as a competitive and sustainable alternative to conventional synthetic surfactants in industrial and consumer applications.

Discussion

The results of this study demonstrate that the biosurfactant produced by *Pseudomonas putida* ICCF 391 using a mixed substrate of glycerol and waste cooking oil exhibits functional properties compatible with circular economy-oriented bioprocesses. The ability to convert waste-derived substrates into a stable and bioactive compound highlights the potential of microbial biotechnology to support waste valorization strategies and to reduce the environmental impacts associated with the uncontrolled disposal of lipid-rich residues, such as waste cooking oil.

By integrating low-value by-products into the biosurfactant production process, this approach contributes to improved resource efficiency while decreasing reliance on conventional, non-renewable raw materials. Such waste-to-resource pathways are consistent with circular bioeconomy principles, as they promote material reuse and enhance the sustainability of industrial supply chains. Furthermore, the utilization of renewable substrates supports diversification away from petrochemical-based surfactant production, which remains associated with environmental persistence and increased ecological risk.

Beyond the sustainability of the production process, the properties of the biosurfactant itself are relevant for applications where environmental compatibility and product performance are essential. The observed stability across a wide range of temperatures and pH values supports its potential use in industrial formulations exposed to variable processing conditions. In addition, the demonstrated antibacterial activity against *Pseudomonas aeruginosa* indicates that this biosurfactant may provide functional benefits in formulations

requiring antimicrobial performance, including cleaning agents, cosmetic products, and sanitation-related applications.

The biodegradability and reduced toxicity commonly associated with microbial biosurfactants further enhance their suitability for applications involving direct or indirect human exposure. By limiting the persistence of surfactant residues in aquatic and terrestrial environments, biosurfactants can mitigate ecological risks while supporting the development of safer consumer products. Accordingly, the biosurfactant evaluated in the present study is consistent with European policy objectives that promote the use of safer chemical alternatives, improved environmental performance, and responsible resource management.

The waste-based production, and antibacterial activity of the biosurfactant from *Pseudomonas putida* ICCF 391 make it a promising candidate for sustainable industrial applications. Its integration into circular economy-oriented production systems may help reduce environmental impact while facilitating the shift toward bio-based, consumer-focused markets (Kumari et al., 2023; Ali et al., 2024).

Conclusions

This study demonstrates that the biosurfactant produced by *Pseudomonas putida* ICCF 391 using waste cooking oil and glycerol as substrates exhibits physico-chemical stability and notable antibacterial activity. These characteristics make it a viable and sustainable substitute for traditional synthetic surfactants. Its production pathway aligns with circular economy principles by converting waste materials into high-value bioproducts, mitigating environmental pollution, and promoting resource efficiency. Furthermore, the biodegradability, low toxicity, and antimicrobial activity of the biosurfactant contribute to the development of safer formulations and reinforce consumer protection. Overall, these findings underscore the biosurfactant's potential for application in green industrial processes and its relevance for policy initiatives promoting sustainable and consumer-oriented markets.

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ENGAGING CONSUMERS AND FIRMS THROUGH CIRCULAR BUSINESS MODELS: FROM AWARENESS TO SUSTAINABLE ACTION

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Abstract

The transition toward a circular economy requires not only technological and organizational innovation, but also active engagement of consumers and business partners. Although circular economy principles emphasize resource efficiency, reuse, and closed-loop systems, their successful implementation depends on how firms design business models that translate sustainability objectives into tangible value for users and stakeholders. In this context, circular business models represent a key mechanism for aligning environmental goals with market expectations and consumer behavior. Existing research indicates that awareness of circular economy principles does not automatically lead to adoption or long-term behavioral change. Instead, the transition from linear to circular practices is shaped by the interaction of communication strategies, business model adaptation, and gradual changes in consumer perceptions and routines. Business models therefore play a dual role by structuring value creation and capture while simultaneously influencing consumer engagement with products, services, and circular practices. Despite growing academic interest, the literature often treats consumer behavior, business model design, and communication mechanisms as separate domains. In addition, diffusion-of-innovation approaches tend to focus on consumer segments without explicitly considering the role of business model transformation in enabling mainstream adoption. This fragmentation limits understanding of how circular solutions move from early awareness to sustained use. To address this gap, this paper examines how circular business models engage consumers and firms across different stages of adoption. By integrating insights from circular economy research, business model frameworks, and diffusion-of-innovation theory, the study proposes a conceptual framework that supports the transition from awareness to sustainable action.

Key words: *Circular business models; Consumer engagement; Business model innovation; Circular economy; Sustainable consumption; Adoption phases; Diffusion of innovation.*

Introduction

Developed economies and, increasingly, leading global companies are adopting the circular economy as a response not only to environmental pressures, but also to changing consumer expectations and market behavior. At its core, the circular economy is guided by the 3R principles (reducing, reusing, and recycling) which directly influence how products are designed, consumed, and returned into economic cycles. Beyond environmental benefits,

circular practices generate economic value through cost savings, extended product lifecycles, and reduced waste generation, creating incentives for both businesses and consumers to change established linear consumption patterns.

The implementation of circular economy principles relies on the adoption of appropriate business models that translate sustainability goals into concrete organizational and market practices. Business models serve as analytical tools that explain how companies create, deliver, and capture value, and they play a critical role in shaping interactions between firms, customers, and other stakeholders (Giourka et al., 2019). In this context, circular business models function as mechanisms that enable behavioral change by redefining value propositions, customer relationships, and consumption practices.

To successfully implement circular economy principles, managers must integrate value creation, value delivery, and value capture while actively engaging consumers and business partners. Three key factors influence this process: the role of policymakers and international institutions in setting regulatory and incentive frameworks; organizational and technological capabilities, including the support of Industry 4.0 technologies, which facilitate transparency, traceability, and resource efficiency; and continuous monitoring of circular performance to ensure long-term behavioral and organizational change (Guldmann, 2016).

Despite growing awareness, several barriers continue to hinder the transition from circular economy concepts to practical implementation. These challenges include limited access to reliable data, insufficient technological infrastructure, weak economic incentives, inconsistent regulatory enforcement, and low levels of consumer awareness and engagement (Korhonen et al., 2017). While existing literature provides guidance on adapting traditional business models to circular principles, there remains a lack of clarity on how these principles can be systematically embedded across all components of a business model framework. This gap highlights the need for a comprehensive conceptual approach that supports companies in engaging consumers and stakeholders and transforming awareness of circular economy principles into sustainable business and consumption practices (Lacy, 2014).

Value creation, value delivery, and value capture represent the core dimensions through which circular business models influence both organizational strategies and consumer behavior. Considering these dimensions raises a critical question: can circular business models serve as practical tools for guiding companies and societies from awareness to concrete action in the transition toward a circular economy?

To better understand how awareness of circular economy principles can be translated into concrete business practices and behavioral change among consumers, it is necessary to examine the tools companies use to design and communicate value. One of the most widely applied frameworks for this purpose is the Business Model Canvas (BMC), which provides a structured overview of how organizations create, deliver, and capture value. Comparing the traditional Business Model Canvas with its circular extension enables a clearer understanding of how business models can actively engage consumers and businesses in circular practices.

In the European policy context, consumer engagement has become a central pillar of the circular economy transition. Recent initiatives, including the European Green Deal and the Circular Economy Action Plan, emphasize not only sustainable production but also informed, empowered, and protected consumers as active participants in circular systems. Consumer rights related to durability, reparability, transparency, and access to information are increasingly recognized as key enablers of circular practices.

From this perspective, circular business models serve as an operational bridge between regulatory objectives and everyday consumption practices. By embedding consumer rights into value propositions, communication strategies, and product–service systems, firms can

reduce information asymmetries and lower perceived risks associated with circular solutions. This alignment is particularly important for overcoming consumer skepticism and fostering trust, which are frequently identified as barriers to adoption. Consequently, understanding how business models integrate consumer rights and engagement mechanisms is essential for translating policy ambitions into market-level outcomes.

In recent years, the transition toward a circular economy has become one of the central priorities of sustainable development policies worldwide. Growing concerns regarding climate change, resource scarcity, environmental degradation, and increasing waste generation have challenged the long-established linear model of economic development based on the "take–make–dispose" principle. While this traditional model has contributed to economic growth for decades, it has also resulted in excessive resource consumption, environmental pollution, and significant pressure on natural ecosystems. As a consequence, governments, international organizations, and businesses are increasingly recognizing that sustainable economic growth requires systemic changes in the way products are designed, produced, consumed, and recovered.

The circular economy has therefore emerged as a comprehensive framework aimed at maintaining the value of products, materials, and resources for as long as possible while minimizing waste generation throughout the entire product lifecycle. Rather than focusing exclusively on recycling, circular economy principles promote preventive strategies such as product durability, repairability, remanufacturing, reuse, and sharing models that reduce the need for continuous extraction of virgin resources. These principles not only contribute to environmental sustainability but also create opportunities for economic value creation, innovation, and improved competitiveness. Consequently, the transition toward circular systems is increasingly viewed as a strategic opportunity rather than solely an environmental obligation.

At the European level, this transition has been strongly supported through policy initiatives such as the European Green Deal and the Circular Economy Action Plan, both of which emphasize the importance of redesigning production and consumption systems to achieve climate neutrality and sustainable economic development. These initiatives highlight that businesses are expected to move beyond compliance with environmental regulations and actively integrate circular principles into their long-term strategies. At the same time, consumers are no longer perceived as passive recipients of products and services but as active participants whose purchasing decisions, usage patterns, and disposal behavior significantly influence the effectiveness of circular systems.

Within this context, business models have gained increasing attention because they determine how organizations translate sustainability objectives into market-oriented solutions. While technological innovations remain essential for improving resource efficiency, technological advancement alone cannot ensure successful circular transitions. Organizations must simultaneously redesign the mechanisms through which value is created, delivered, and captured while encouraging customers to adopt new forms of consumption based on access, sharing, repair, and product life extension. This shift requires companies to reconsider not only operational processes but also relationships with customers, suppliers, and other stakeholders across the value chain.

Consumer participation has consequently become one of the most important determinants of circular economy implementation. Numerous circular initiatives fail to achieve their intended impact because consumers often remain reluctant to modify established consumption habits despite expressing positive environmental attitudes. Previous studies repeatedly demonstrate that awareness of sustainability issues does not necessarily translate

into behavioral change. Instead, adoption depends on multiple factors, including trust, convenience, perceived value, economic incentives, social influence, and the effectiveness of organizational communication. This discrepancy between environmental awareness and actual participation highlights the importance of designing business models capable of reducing perceived risks while increasing consumer confidence in circular products and services.

From this perspective, circular business models should not be understood merely as organizational frameworks for managing resources but as mechanisms that actively facilitate interaction between companies and consumers throughout the product lifecycle. By integrating communication strategies, service innovation, reverse logistics, and customer engagement into a unified system, circular business models create conditions under which sustainable behavior becomes easier, more accessible, and economically attractive. Such an approach moves beyond viewing sustainability as an isolated organizational objective and instead positions it as a shared responsibility among businesses, consumers, policymakers, and society as a whole.

Despite the rapidly expanding body of literature on circular economy and sustainable business models, important conceptual gaps remain. Existing studies frequently examine business model innovation, consumer engagement, communication strategies, and diffusion-of-innovation processes separately, without adequately explaining how these dimensions interact over time during the transition toward circular practices. As a result, there is still limited understanding of how organizations can systematically transform initial consumer awareness into widespread adoption and long-term behavioral change. Addressing this gap requires a more integrated conceptual perspective capable of linking organizational design, stakeholder engagement, and consumer behavior within a single analytical framework.

Business Model Frameworks for Engaging Consumers and Businesses in Circular Practices

A business model describes the underlying logic through which an organization creates value, delivers it to the market, and captures economic returns (Osterwalder & Pigneur, 2010). In contemporary research, business models are increasingly viewed as dynamic constructs that support organizational transformation, particularly in periods of strategic change and innovation (De Reuver et al., 2013; Murray & Scuotto, 2016). Transitioning from an existing business model to a new one represents a complex managerial challenge, as it requires redefining value propositions, acquiring new resources and capabilities, and reconsidering existing partnerships and stakeholder relationships.

From a strategic perspective, business models also function as analytical tools that support decision-making and organizational positioning. Previous studies have demonstrated that the Business Model Canvas can be combined with complementary strategic instruments, such as SWOT analysis, to identify weaknesses and threats and translate them into actionable development strategies (Mustaniroh et al., 2020). This highlights that business models are not static descriptions of firm activity, but flexible frameworks that can be used to align internal capabilities with external market and stakeholder expectations.

Structure of the Business Model Canvas

One of the most widely applied frameworks for structuring business models is the Business Model Canvas (BMC), developed by Osterwalder and Pigneur. The BMC provides a visual and systematic representation of how organizations organize value creation, value delivery, and value capture through nine interrelated building blocks. This structure enables firms to

assess how value propositions are communicated to customers and how relationships with key stakeholders are established and maintained.

By integrating key elements such as customer segments, value propositions, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, and cost structure, the BMC offers a holistic overview of organizational logic and strategic priorities. Its visual format facilitates internal communication, strategic alignment, and iterative refinement of business models, particularly in contexts characterized by innovation and market uncertainty.

In addition, the BMC supports comparative analysis by allowing organizations to evaluate existing business models and explore alternative configurations. As such, it is widely used not only as a descriptive tool, but also as a decision-support framework that helps managers identify opportunities for innovation, improve value delivery mechanisms, and adapt to changing market and stakeholder expectations.

In increasingly dynamic and competitive markets, organizations are required to continuously adapt their business models to changing customer expectations, technological developments, and sustainability challenges. The rapid digitalization of business processes, globalization of markets, and growing emphasis on environmental responsibility have significantly transformed the way firms create and deliver value. Under these conditions, companies are no longer expected to compete solely through products or services but through innovative business models that effectively integrate customer needs, organizational capabilities, and strategic partnerships. Consequently, business model design has become one of the central managerial tools for achieving competitive advantage and supporting long-term organizational growth.

Among the various frameworks proposed for business model development, the Business Model Canvas (BMC) has emerged as one of the most widely adopted approaches in both academic research and managerial practice (Osterwalder & Pigneur, 2010). The popularity of the framework stems from its ability to provide a clear and visual representation of how organizations create, deliver, and capture value while simultaneously illustrating the interdependencies among key business components. Unlike traditional business planning documents, which often focus on financial projections and operational details, the Business Model Canvas emphasizes the strategic logic underlying business activities and facilitates communication among managers, entrepreneurs, and other stakeholders.

The Business Model Canvas is particularly valuable for innovative firms operating in uncertain environments because it encourages experimentation, continuous adaptation, and customer-oriented thinking. Rather than viewing business models as static organizational structures, the framework supports an iterative process in which firms continuously evaluate and redesign their value propositions in response to market feedback. This characteristic makes the Business Model Canvas especially suitable for start-ups, technology-based companies, and organizations undergoing strategic transformation.

According to Osterwalder and Pigneur (2010), the Business Model Canvas consists of nine interconnected building blocks, each representing a fundamental aspect of organizational value creation. These elements collectively explain how a company generates value for customers while ensuring long-term economic sustainability.

The first component, Customer Segments, identifies the specific groups of customers that an organization intends to serve. Understanding customer characteristics, preferences, and needs enables firms to develop tailored solutions that address market demands more effectively.

The Value Proposition represents the central element of the framework by defining the bundle of products and services that create value for customers. It explains why customers choose one organization over another by highlighting unique benefits, problem-solving capabilities, and opportunities for creating additional value.

Channels describe how organizations communicate with customers, deliver products and services, and maintain interactions throughout the customer journey. Effective channels ensure that value propositions reach the intended market efficiently while supporting customer satisfaction.

The Customer Relationships block focuses on the type of relationships organizations establish with different customer segments. These relationships may range from personalized assistance to automated services and community-based interactions, depending on strategic objectives and customer expectations.

The financial dimension of the model is represented through Revenue Streams, which explain how organizations generate income from different customer segments. Revenue may originate from direct product sales, subscriptions, licensing agreements, leasing arrangements, or other innovative pricing mechanisms.

The operational foundation of the business model is reflected in Key Resources and Key Activities. Key resources include the physical, intellectual, financial, and human assets necessary for delivering value, whereas key activities represent the critical processes that enable organizations to develop products, provide services, and maintain competitive performance.

The Key Partnerships block emphasizes the importance of collaboration with suppliers, strategic partners, research institutions, and other stakeholders who contribute complementary resources and capabilities. In increasingly interconnected markets, partnerships frequently become essential for innovation, risk sharing, and access to new markets.

Finally, Cost Structure summarizes the major costs associated with implementing the business model, including investments in key resources, operational activities, partnerships, and customer relationships. Understanding cost drivers enables organizations to balance value creation with economic efficiency and long-term profitability.

Because all nine building blocks are interconnected, modifications in one component often influence the entire business model. Consequently, the Business Model Canvas should not be viewed as a static planning instrument but rather as a dynamic managerial framework that supports continuous innovation, organizational learning, and strategic adaptation. This holistic perspective has also provided the foundation for the development of several specialized extensions, including the Value Proposition Canvas and, more recently, the Circular Business Model Canvas, which further expand the original framework by incorporating customer-centric and sustainability-oriented dimensions (Lewandowski, 2016; Sibalija et al., 2021).

Circular Business Model Canvas as a Mechanism for Circular Action

The Circular Business Model Canvas represents an extended version of the traditional Business Model Canvas, redesigned to reflect the principles and logic of the circular economy. Rather than focusing solely on linear value creation, this framework emphasizes closed-loop systems, long-term resource use, and active stakeholder participation. By expanding the original canvas structure, the model introduces additional elements that explicitly address consumer involvement, resource recovery, and organizational readiness for circular transformation (Lewandowski, 2016).

The framework comprises a set of interconnected components that collectively support the design and implementation of circular-oriented business models. These elements guide organizations in translating sustainability awareness into operational practices and behavioral change across the value chain.

- **Circular value offerings** focus on products and services designed for durability, reuse, repair, and shared use, often supported by incentive mechanisms that encourage customers to return products after use.
- **Target user groups** are defined in close alignment with circular value offerings, ensuring that products and services correspond to user needs, usage patterns, and sustainability expectations.
- **Interaction and distribution channels** include both digital and physical pathways that facilitate access to circular products and enable continuous communication with users throughout the product lifecycle.
- **Engagement-oriented customer relationships** prioritize demand-driven production, social marketing, and collaboration with communities and local stakeholders, particularly in advanced recycling and reuse systems.
- **Circular revenue logic** is based on access, performance, or usage rather than ownership, with additional value generated through recovered materials and reintegrated resources.
- **Strategic resources** emphasize renewable, high-quality, and recoverable materials, as well as the regeneration of natural capital and the integration of customer-owned or third-party resources into closed loops.
- **Operational activities** include efficiency improvements, technological innovation, product redesign for recyclability, and organizational actions that support circular transition, including advocacy and stakeholder coordination.
- **Collaborative partnerships** are formed with supply chain actors and value network participants who actively contribute to circular objectives.
- **Cost configuration** reflects the specific financial dynamics of circular systems, including investments in return mechanisms, incentives, and monitoring processes, often requiring adapted accounting approaches.
- **Return and recovery systems** are explicitly incorporated to manage product take-back, reverse logistics, and user participation in reuse and recycling processes.
- **Adoption and enabling conditions** capture both internal organizational capabilities and external institutional, regulatory, and market-related factors that influence the successful implementation of circular business models.

Together, these elements ensure that circular principles are embedded across the entire value chain, positioning the Circular Business Model Canvas as a practical tool for engaging consumers and businesses in sustainable and circular practices (Lewandowski, 2016).

The Circular Business Model Canvas serves as a foundational mechanism through which consumer engagement is operationalized across different stages of adoption. By integrating communication channels, engagement-oriented customer relationships, and return and recovery systems, the CBMC supports the gradual transition from awareness to adoption and stabilization. This perspective highlights the role of business model design as an active driver of consumer participation and behavioral change in circular business model transitions.

Beyond its structural role, the Circular Business Model Canvas provides a practical lens for understanding how firms can actively engage consumers in circular practices. Several CBMC components directly shape consumer participation by influencing how users access, use, and return products and services. Engagement-oriented customer relationships, access-

based revenue models, and return and recovery systems transform consumers from passive buyers into active contributors within circular value chains.

These mechanisms support behavioral change by lowering participation barriers and reinforcing learning processes over time. For example, take-back schemes and repair services encourage repeated interaction, while transparent communication channels enhance consumer understanding of product lifecycles and environmental impacts. Incentive structures linked to reuse and return further strengthen motivation and commitment.

As a result, the CBMC can be interpreted not only as a design framework for circular value creation, but also as a behavioral interface that aligns business model elements with everyday consumption routines. This perspective highlights the role of business model design as an active driver of consumer engagement, rather than a static organizational blueprint. Such an interpretation provides a conceptual foundation for examining how circular business models facilitate transitions from awareness to adoption and, ultimately, to long-term stabilization of circular practices.

Business Model Transformation from Linear to Circular Practices

This comparison highlights how the transition from traditional to circular business models requires not only structural changes in business design, but also active engagement of consumers and businesses in circular practices.

<i>BMC Building Block</i>	<i>Traditional Business Model (BM)</i>	<i>Circular Business Model (CBM)</i>
<i>Customer Segments</i>	Customers defined mainly by demand and purchasing power	Customers viewed as users and co-participants in circular practices
<i>Value Proposition</i>	Product ownership and functional value	Extended product life, access-based value, repair, reuse, and sustainability benefits
<i>Channels</i>	Primarily physical or sales-oriented channels	Integrated physical and digital channels supporting communication, use, and return
<i>Customer Relationships</i>	Transaction-based and short-term	Long-term engagement, education, and behavior-oriented interaction
<i>Revenue Streams</i>	One-time sales and ownership transfer	Subscription, pay-per-use, leasing, and value from recovered resources
<i>Key Resources</i>	Virgin materials and internally owned assets	Renewable, recyclable, and shared resources within closed loops
<i>Key Activities</i>	Production, marketing, and distribution	Lifecycle management, product redesign, recovery, and monitoring
<i>Key Partnerships</i>	Supplier-focused and cost-driven	Ecosystem partnerships enabling circular flows and shared responsibility
<i>Cost Structure</i>	Focus on production and logistics cost efficiency	Costs related to take-back systems, incentives, monitoring, and circular infrastructure

Table 1. Comparison of the Traditional Business Model Canvas and the Circular Business Model Canvas

Table 1 provides a comparative overview of the traditional Business Model Canvas and the Circular Business Model approach across the nine core building blocks. The comparison highlights how circular business models redefine value propositions, customer relationships, and resource use by actively engaging consumers and partners in circular practices. By emphasizing lifecycle management, closed-loop resource flows, and long-term stakeholder engagement, the circular model illustrates the shift from awareness of sustainability issues toward concrete behavioral and organizational action.

Consumer and Business Engagement Mechanisms in Circular Models

Previous studies emphasize that effective circular transitions require the alignment of consumer behavior, business model design, and communication mechanisms. In this context, circular business models can be understood as integrative frameworks that coordinate these domains and support the shift from sustainability awareness to practical engagement (Gomes et al., 2024).

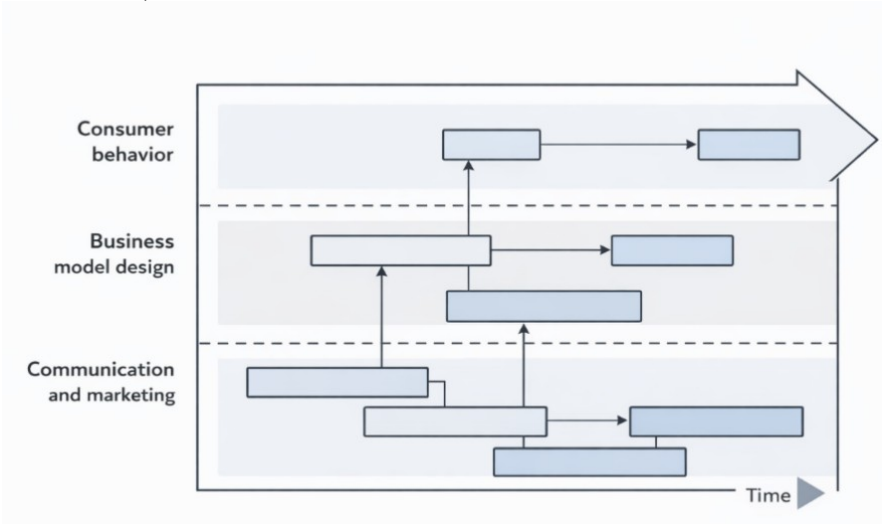


Figure 1. Conceptual interaction between communication & marketing, business model design, and consumer behavior over time (Gomes et al., 2024)

Figure 1 illustrates the dynamic and time-dependent relationship between communication and marketing activities, business model design, and consumer behavior. The model highlights communication and marketing as initial drivers of change, which stimulate adaptations in business model design. These adaptations subsequently influence consumer behavior, with a noticeable time lag. The dashed horizontal lines distinguish the three analytical levels, while vertical arrows indicate the direction of influence between them. Overall, the figure emphasizes the iterative and non-linear nature of circular business model transitions, where sustained communication efforts and business model adjustments are required before observable changes in consumer behavior occur.

The literature suggests that the successful adoption of circular business models depends not only on structural design choices, but also on how effectively consumer practices are integrated into the business model. Factors such as convenience, economic incentives, and opportunities for co-design have been identified as critical in motivating consumer

participation, highlighting the importance of aligning business model elements with everyday consumption practices. (Borrello et al., 2020)

In addition to business model design, communication plays a central role in transforming awareness into action. Clear, transparent, and practice-oriented communication helps consumers understand their role within circular systems, particularly in activities related to repair, reuse, and recycling. Digital channels, labeling, and feedback mechanisms can support learning and reinforce sustainable behavior by making circular practices visible and accessible to users.

From the business perspective, active engagement mechanisms such as take-back schemes, repair services, and participation incentives enable firms to move beyond passive sustainability messaging. By embedding these mechanisms directly into customer relationships and value propositions, companies can encourage repeated interaction and long-term commitment to circular practices. This approach strengthens business–consumer relationships and increases the likelihood of sustained participation in circular business models.

In the context of circular business models, consumer engagement is closely linked to the protection and empowerment of consumer rights. Rights related to access to information, product durability, reparability, and transparency play a crucial role in shaping consumer willingness to participate in circular practices. When consumers clearly understand how products can be reused, repaired, or returned, engagement mechanisms become more effective and trust in circular systems increases.

Moreover, engagement should not be understood as a one-time interaction, but as an ongoing process that evolves throughout the product lifecycle. Communication tools, feedback mechanisms, and participatory design approaches enable consumers to actively contribute to circular value creation. This continuous interaction supports learning processes and facilitates the internalization of circular practices, thereby strengthening the transition from awareness to sustained behavioral change.

A Multilevel Consumer Adoption Framework for Circular Business Model Transitions

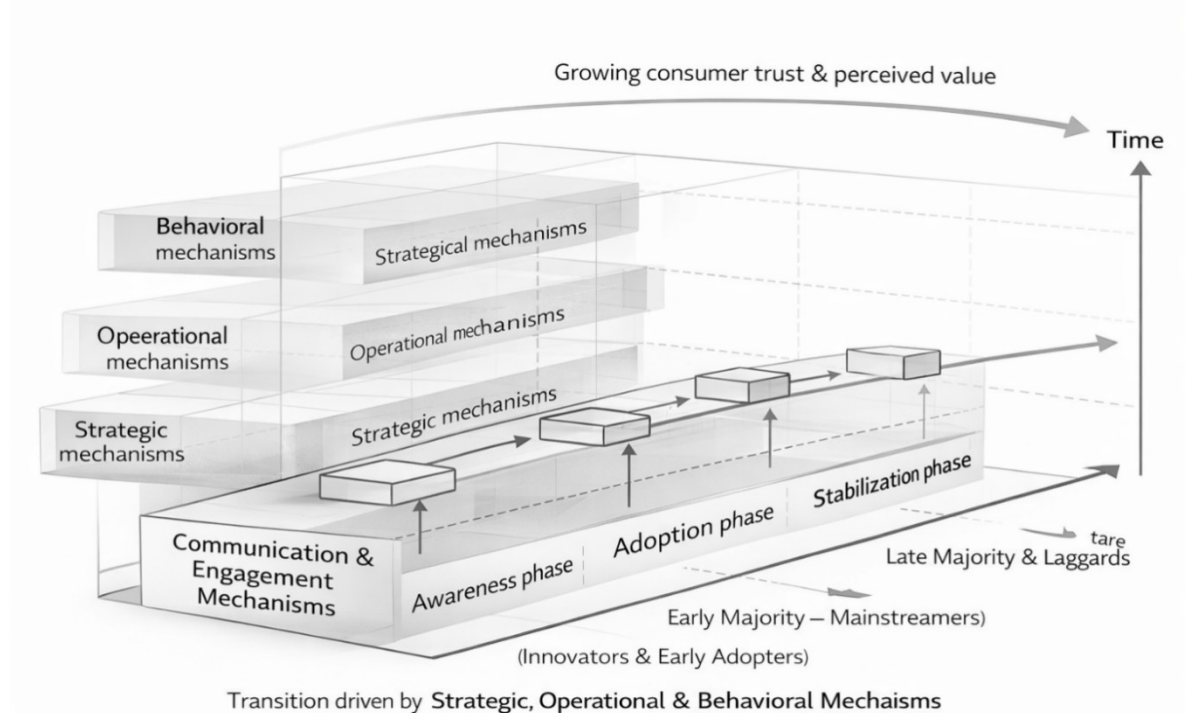


Figure 2. Three-dimensional conceptual framework illustrating the transition of circular business models over time. The model integrates temporal adoption phases (awareness, adoption, stabilization), multi-level interactions (communication and engagement mechanisms, business model design, consumer behavior), and innovation transition mechanisms (strategic, operational, and behavioral). The adoption phase corresponds to the transition toward mainstream adoption, aligning the framework with diffusion-of-innovation theory. Adapted from prior literature.

Figure 2 presents an integrated, three-dimensional conceptual framework illustrating how circular business model transitions unfold over time through the interaction of communication and engagement mechanisms, business model adaptation, and consumer behavioral change. The model aligns the temporal phases of awareness, adoption, and stabilization with diffusion-of-innovation logic and embeds them within strategic, operational, and behavioral transition mechanisms.

The adoption phase represents a critical transition point in circular business model diffusion, as it marks the shift from early adopters to mainstream consumers. While innovators and early adopters are often motivated by environmental values and experimentation, mainstream consumers tend to prioritize convenience, reliability, and perceived value. This difference explains why many circular initiatives struggle to scale beyond niche markets.

Within this phase, business model adaptation and communication mechanisms play a decisive role in reducing uncertainty and perceived risk. Clear value propositions, transparent pricing models, and accessible service infrastructures help normalize circular practices and integrate them into everyday routines. At the same time, consumer feedback and usage data enable firms to refine offerings and improve usability, reinforcing a positive feedback loop between adoption and business model design.

By explicitly positioning the adoption phase as a transition toward mainstream acceptance, the proposed framework advances diffusion-of-innovation theory by highlighting the mediating role of business models. This approach shifts attention from consumer segmentation alone toward the interaction between business model configuration and consumer behavior, offering a more nuanced explanation of how circular solutions achieve scale.

Building on prior research on circular business models and diffusion-of-innovation theory, this study proposes an integrated temporal–multilevel adoption framework to explain how circular business models transition from early awareness to mainstream acceptance and long-term stabilization. As illustrated in Figure 2, the framework combines three analytical levels—communication and engagement mechanisms, business model design, and consumer behavior—across three temporal phases: awareness, adoption, and stabilization. While existing studies often examine these dimensions in isolation, the proposed model emphasizes their dynamic interaction over time. In line with diffusion-of-innovation literature, the awareness phase is primarily driven by innovators and early adopters, whereas the adoption phase represents the critical transition toward mainstream acceptance by the early majority. The stabilization phase reflects the routinization of circular practices among the late majority and laggards. Unlike linear adoption models, this framework embeds these temporal phases within strategic, operational, and behavioral transition mechanisms, highlighting how communication intensity, business model reconfiguration, and consumer learning jointly contribute to increasing trust and perceived value. By integrating temporal dynamics, multi-level interactions, and innovation transition mechanisms into a unified three-dimensional framework, this model extends existing circular business model literature and offers a more comprehensive explanation of how circular solutions achieve sustained consumer adoption.

The proposed multilevel adoption framework provides an integrative perspective that goes beyond existing linear or single-level approaches to circular business model adoption. By explicitly combining temporal phases, multi-level interactions, and innovation transition mechanisms, the framework captures the complexity of real-world circular transitions.

In particular, the integration of strategic, operational, and behavioral mechanisms highlights that successful adoption depends not only on consumer motivation, but also on how firms design supportive infrastructures and engagement pathways. This perspective allows researchers and practitioners to better identify bottlenecks in the adoption process and to design targeted interventions that facilitate the transition from early adoption to long-term stabilization.

Discussion and practical implications

The proposed conceptual framework contributes to the growing body of literature on circular business models by integrating three research streams that are often examined independently: business model innovation, consumer engagement, and diffusion-of-innovation theory. While previous studies have extensively discussed the structural characteristics of circular business models and the importance of sustainable consumption, relatively limited attention has been devoted to explaining how these elements interact dynamically over time. By combining temporal adoption phases with business model adaptation and communication mechanisms, the proposed framework offers a more comprehensive understanding of the transition from awareness to sustained circular behavior.

One of the principal theoretical contributions of this study lies in positioning business models as active mechanisms that shape consumer adoption rather than merely describing

organizational structures. Traditional business model research has primarily focused on value creation, value delivery, and value capture from the organizational perspective. However, within circular economy contexts, business models also perform an educational and behavioral function by reducing uncertainty, facilitating participation, and encouraging long-term engagement. This perspective extends existing business model literature by emphasizing the interaction between organizational design and consumer decision-making processes.

From a managerial perspective, the framework highlights that successful implementation of circular business models depends not only on technological innovation but also on the ability of organizations to design customer experiences that facilitate participation in circular practices. Firms should therefore invest in transparent communication, user-friendly digital platforms, repair and maintenance services, take-back systems, and incentive mechanisms that lower participation barriers. Such initiatives increase consumer confidence while simultaneously improving the long-term viability of circular business models.

The framework also underlines the importance of collaboration across multiple stakeholder groups. Circular business models require coordinated actions involving manufacturers, suppliers, consumers, policymakers, recycling organizations, and digital service providers. Building effective partnerships enables organizations to develop integrated value networks capable of supporting resource recovery, product life extension, and closed-loop material flows. Consequently, collaboration becomes a strategic capability rather than merely an operational requirement.

For policymakers, the proposed framework demonstrates that regulatory initiatives alone are insufficient to accelerate circular economy adoption. Legislative measures should be complemented by educational campaigns, financial incentives, digital infrastructure, and policies that strengthen consumer trust through transparency and access to reliable information. Initiatives promoting product durability, reparability, and the right to repair may significantly enhance consumer participation while simultaneously encouraging firms to redesign their business models according to circular economy principles.

Finally, although the proposed framework remains conceptual, it provides a foundation for future empirical research. Researchers may examine how individual business model components influence different stages of consumer adoption across industries, countries, and cultural contexts. Longitudinal studies could further investigate how communication strategies, technological innovation, and organizational learning jointly contribute to the long-term stabilization of circular consumption systems.

Conclusions

This paper explored the role of circular business models as mechanisms for engaging consumers and firms in the transition from sustainability awareness to sustained circular practices. By examining the structure of the traditional Business Model Canvas and its circular extension, the study highlighted how circular business models redefine value propositions, customer relationships, and resource use in ways that actively involve users and partners throughout the product lifecycle.

Building on this foundation, the proposed integrated temporal–multilevel adoption framework advances existing literature by linking business model design, communication and engagement mechanisms, and consumer behavior within a unified conceptual structure. By aligning the phases of awareness, adoption, and stabilization with diffusion-of-innovation logic, the framework emphasizes the critical role of the adoption phase as the transition toward mainstream acceptance of circular solutions. The inclusion of strategic, operational,

and behavioral mechanisms further illustrates how trust, perceived value, and learning processes evolve over time and support long-term stabilization.

The study contributes to circular business model research by moving beyond static representations and highlighting the dynamic and non-linear nature of adoption processes. From a practical standpoint, the framework offers guidance for managers and policymakers by illustrating how communication strategies and business model configurations can be coordinated to foster consumer engagement and sustained participation in circular systems.

The findings underline the importance of aligning business model innovation with consumer engagement strategies. Managers designing circular business models should prioritize communication clarity, ease of participation, and trust-building mechanisms, particularly during the adoption phase. Embedding repair, reuse, and return options into customer journeys can significantly enhance long-term engagement and stabilize circular practices.

For policymakers, the framework highlights the need to support business model experimentation through regulatory incentives, standardization efforts, and consumer protection measures. Policies that promote transparency, durability, and right-to-repair can reinforce business-led engagement mechanisms and accelerate mainstream adoption. By coordinating policy interventions with business model innovation, institutional actors can strengthen the conditions under which circular solutions move from awareness to sustained market integration.

Future research could empirically test the proposed framework across different industries and geographical contexts, as well as examine how specific engagement mechanisms influence adoption dynamics. Such research would further enhance understanding of how circular business models can effectively support the transition toward a more sustainable and circular economy.

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DATA - DRIVEN ASSESSMENT OF CIRCULAR ENERGY EFFICIENCY: AN EXPLAINABLE AI APPROACH

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Abstract

This paper presents an operational, closed-loop-inspired framework for assessing circular energy efficiency in district heating systems using real Supervisory Control and Data Acquisition (SCADA) data. Inefficiencies are characterized through regime-dependent “wastage signatures” (elevated supply/return temperatures, low ΔT , and control-induced mismatches).

As a baseline of expected consumption for the Lamella L17 substation (Faculty of Mechanical Engineering, University of Nis), we train ensemble models - Random Forest and Least-Squares Boosting on time-aligned measurements (outdoor temperature, secondary-side supply temperature, and delivered heat), augmented with temporal features and short-horizon lags. Evaluation with a chronological train/test split shows that Random Forest provides the most robust performance (RMSE = 3.85, MAE = 1.67, R^2 = 0.894), particularly during abrupt regime changes.

An explainability layer (permutation importance) is then applied to identify dominant drivers and flag high-deviation episodes as candidates for inefficient operation. The proposed workflow links baseline forecasting, interpretable diagnostics, and intervention-oriented feedback to support continuous efficiency improvement and more reliable heat delivery.

Key words: *district heating, circular energy efficiency, machine learning, explainable artificial intelligence*

Introduction

Circular energy efficiency in thermal energy systems can be interpreted as the systematic identification and reduction of resource dissipation across the full value chain - generation, the distribution network, and end-use - while maximizing the utilization of useful heat,

including waste heat and low-temperature sources. In district heating (DH), circularity is typically reflected in operational symptoms such as unnecessarily high supply temperatures, unfavorable return temperatures, low temperature difference (ΔT), and excessive mass flows, which jointly increase distribution and pumping losses and may degrade service quality. Because these inefficiencies are strongly regime-dependent (e.g., seasonal transitions, load ramps, partial-load operation, and network constraints), an actionable circular-efficiency assessment requires methods that are accurate, computationally feasible, and transparent to operational stakeholders.

In practice, DH operators already have extensive measurement infrastructure (e.g., SCADA, substation heat meters, temperature sensors, and in some cases building-level signals). However, translating these streams into continuous improvement actions is not straightforward. Raw measurements can confirm that a deviation occurred (e.g., rising return temperature or collapsing ΔT), but they do not, on their own, explain whether the deviation is demand-driven, caused by control logic, driven by hydraulic limitations, or linked to end-user behavior. Moreover, high-frequency or irregularly sampled operational data often exhibit missingness, regime switching, and delayed effects, making purely physics-based supervisory diagnostics difficult to maintain at scale. Consequently, the methodological challenge is not only to predict and detect deviations, but also to produce interpretable, regime-aware evidence that supports operational decisions, intervention design, and subsequent evaluation.

The recent DH literature provides the necessary building blocks for such an assessment, spanning reduced-order and data-driven representations that enable scalable deployment (Kudela et al., 2020; Rein et al., 2020), short-term forecasting as an operational baseline (Maryniak et al., 2024; Potočník et al., 2021), explainability methods to diagnose the drivers of inefficiency (Neubauer et al., 2025), and optimization/control strategies to test and implement interventions (Schindler et al., 2023; Vesterlund and Toffolo, 2017; Stock et al., 2024). In parallel, the building-energy community has demonstrated learning-based approaches that are relevant at the consumer interface of DH, including heat-load prediction for buildings connected to DH networks (Hajri et al., 2025), reinforcement-learning-based heating control motivated by cost reduction (Kannari et al., 2023), and adaptive modeling concepts for long-term operation under changing conditions (Chen et al., 2024). These strands are directly relevant to circularity because the main circular “symptoms” in DH are ultimately produced at the interface between network operation and end-use behavior.

However, these components are often treated in isolation. Forecasting is frequently evaluated primarily through error metrics, Explainable Artificial Intelligence (XAI) is used for model interpretation rather than operational diagnosis, and optimization/control is addressed as a standalone objective rather than as part of a measurable efficiency-improvement loop. Similarly, consumer-side learning approaches (e.g., reinforcement learning control or building load prediction) are often discussed as local improvements, without explicit linkage to network-side temperature regimes, return-temperature constraints, or system-level Key Performance Indicators (KPIs) that define circular efficiency in DH. As a result, the field still lacks a unified, operationally oriented workflow that links baseline modeling, interpretable loss signatures, and intervention evaluation into a transparent closed loop suitable for continuous improvement (Kudela et al., 2020; Neubauer et al., 2025; Medina Cruz et al., 2025). Recent applied studies comparing machine-learning methods for DH load

prediction and addressing irregular time-series and explainability themes further support the operational relevance of closed-loop, interpretable assessment workflows (Tasić et al., 2024; Tasić et al., 2025; Tasić et al., 2025b).

COST Action CA22124 - ECO4ALL (Circular Economy that Works for Consumers) is a European research initiative that promotes sustainable development by strengthening the role of consumers in the circular economy. The Action focuses on sustainable consumption, resource efficiency, waste prevention, and consumer protection through evidence-based and cross-country assessment of circular strategies from legal, social, economic, and environmental perspectives. Within the broader context of the ECO4ALL Action, this work contributes to the understanding of how circular-economy principles can be operationalized in energy systems in a way that is meaningful for multiple stakeholders along the value chain, including system operators and end users. ECO4ALL emphasizes the role of consumers, transparency, and data-informed decision-making as prerequisites for effective circularity, moving beyond abstract policy objectives toward measurable and actionable improvements. In district heating systems, operational inefficiencies such as elevated return temperatures, low temperature differentials, and excessive mass flows represent not only technical losses but also a failure to align network operation with end-use behaviour and consumer-level engagement. By developing an interpretable, data-driven workflow for identifying, explaining, and evaluating circular-efficiency losses in DH operation, this study directly supports the ECO4ALL objectives of evidence-based assessment and quantitative measurement of inefficiencies and their drivers, thereby contributing to the design of circular strategies that are transparent, verifiable, and capable of supporting informed interventions at both the system and consumer interfaces.

Related work

Prior work covers complementary building blocks that can be assembled into a closed-loop assessment logic for district heating: scalable/deployable models, forecasting baselines for deviation detection, interpretable diagnostics, and intervention-oriented methods. In addition, related work from building energy management contributes useful concepts at the demand interface, particularly for data-driven load estimation and learning-based control.

A practical prerequisite for continuous assessment is deployability: models must be accurate yet computationally light, robust under data imperfections, and maintainable as operating conditions shift. Kudela et al. (2020) discuss how machine learning can be integrated efficiently into district-heating predictive workflows, with attention to implementation aspects that determine whether a model remains usable outside of a research setting (Kudela et al., 2020). From an assessment perspective, this is significant because a closed-loop efficiency workflow cannot rely on models that are too fragile, too expensive to re-train, or too opaque to validate. In parallel, Rein et al. (2020) show that network control problems become difficult to solve online when full dynamics are included and demonstrate how reduced-order modelling supports tractable optimization while preserving key dynamic constraints (Rein et al., 2020). Together, these contributions motivate a pragmatic stance: circular-efficiency monitoring should build on models that can operate at substation and network scales in near real time, even if they intentionally trade some fidelity for reliability and speed.

Accurate forecasting of heat load and/or heat production is a cornerstone of efficiency assessment because it enables the separation of normal demand variability from operationally induced losses (e.g., overheating, over-supply, and inadequate tracking of demand). Maryniak et al. (2024) demonstrate the use of a neural network for forecasting daily heat production in a district heating plant, emphasizing model validation and the use of performance indicators as a basis for comparing alternative approaches. In the presented case, the authors report an effectiveness of 85% for the trained network (Maryniak et al., 2024), which is relevant to the assessment layer because a stable forecast allows observed deviations to be interpreted as signals of inefficient operation rather than as consequences of inherently unpredictable demand. Potočník et al. (2021) further strengthen this argument by focusing on short-term demand forecasting in district heating, reporting that, for a 48-hour forecast horizon, prediction errors below approximately 3% can be achieved in their scenario (Potočník et al., 2021). Such accuracy levels are particularly important when circular efficiency is operationalized through indicators such as: (1) excess heat delivered relative to an optimum, (2) unnecessarily high temperature regimes, and (3) losses driven by mismatches between supply and demand.

At the end-use interface, forecasting and baseline estimation are equally relevant because building demand is the main driver of supply-temperature decisions and network mass-flow patterns. Hajri et al. (2025) specifically address heat-load prediction for buildings connected to DH networks using data-driven modelling (Hajri et al., 2025). This line of work supports circular-efficiency assessment in two ways: first, it can refine what “normal” demand behaviour looks like for a given building or consumer group; second, it helps localize inefficiency by distinguishing network-driven anomalies from genuine demand changes. In a closed-loop setting, such consumer-level baselines are valuable for diagnosing whether high supply temperatures or poor ΔT arise from network control settings, substation heat exchanger behaviour, or demand-side disturbances.

Although data-driven models can achieve high predictive accuracy, assessing circular efficiency requires more than a “good predictor”: it is necessary to explain which factors - and under which operating regimes - generate resource wastage. This is particularly important in DH systems, where decisions affect costs, emissions, hydraulic conditions, and end-user comfort (Stock et al., 2024). Neubauer et al. (2025) explicitly emphasize interpretability for multi-step heating load forecasting by combining SHapley Additive exPlanations (SHAP)-based attribution with temporal mechanisms, enabling the identification of contributions from individual features and past time steps to the forecast (Neubauer et al., 2025). From an assessment standpoint, the key value of this approach is that XAI makes it possible to link inefficiencies (e.g., episodes of excess supply or unfavourable temperature regimes) to actionable drivers and to form a transparent diagnostic of circular efficiency, rather than relying solely on aggregate accuracy metrics. In operational environments, this diagnostic role is critical: when a KPI indicates deterioration, operators need to understand whether the driver is weather sensitivity, control hysteresis, lagged thermal inertia, abnormal flow conditions, or a shift in consumer-side behaviour.

A closely related practical challenge is non-stationarity: DH systems and connected buildings evolve over seasons, retrofits, occupancy changes, tariff structures, and control updates. Chen et al. (2024) address dynamic and adaptive modelling in building energy

systems through lifelong learning concepts, aiming to sustain model performance under changing conditions (Chen et al., 2024). While their focus is broader than DH alone, the implication for circular-efficiency assessment is direct: a closed-loop workflow must remain valid as the system drifts, otherwise KPI baselines and explainability conclusions become unreliable. Lifelong or adaptive learning strategies can therefore be interpreted as enablers of continuous circular-efficiency monitoring, reducing the need for disruptive re-calibration cycles and supporting more stable decision support.

In literature, optimization and control are often treated as primary objectives; however, within a circular-efficiency framework they can be viewed as a downstream layer—interventions designed only after it has been identified where and why resource wastage occurs. Rein et al. (2020) analyse optimal control of DH networks using a reduced-order model, emphasizing that network dynamics as constraints in the optimization problem make online computation of the optimum difficult without model reduction (Rein et al., 2020). In an assessment context, this work is relevant because it demonstrates how models can be made sufficiently fast to support systematic intervention testing and evaluation of their effects on efficiency indicators. Schindler et al. (2023) consider optimization-driven operation of DH networks Mixed-Integer Linear Programming (MILP), focusing on the integration and coordination of sources in real systems (Schindler et al., 2023). This approach aligns well with circular logic because it enables the evaluation and selection of strategies that increase the utilization of available resources (including local and low-carbon options), while explicitly managing trade-offs among energy, costs, and operational constraints. A common conclusion is that reliable assessment (data-driven and transparent) and optimization should function as a unified chain: (1) measurement/forecasting, (2) identification of losses and their causes, and (3) selection and evaluation of interventions (Rein et al., 2020; Neubauer et al., 2025; Schindler et al., 2023).

At the consumer-control layer, learning-based strategies can also be interpreted as intervention mechanisms. Kannari et al. (2023) study reinforcement-learning-based heating control driven by energy cost considerations (Kannari et al., 2023). Within a DH circular-efficiency narrative, this is relevant because it exemplifies how advanced control can shift operational regimes toward lower losses - provided that the reward structure and constraints reflect DH-specific circular objectives (e.g., penalizing high return temperature, incentivizing higher ΔT , or discouraging excessive mass flows). This highlights a key methodological point for closed-loop assessment: the same measurable KPIs used to diagnose inefficiency should, where possible, be aligned with the objectives and constraints of downstream control and optimization layers, ensuring that interventions target the actual sources of dissipation rather than merely improving local cost or comfort metrics.

In DH systems, circular efficiency largely manifests through return temperature, ΔT , and flow rates, as these determine distribution losses, pumping energy, and the feasibility of integrating low-temperature sources. Tol and Madessa (2024) focus on return-temperature reduction at end-user sites, emphasizing that improvements often rely on actions that affect return temperature and system hydraulics (Tol and Madessa, 2024). Tol and Madessa (2025) further review return-temperature reduction strategies and their role in overall efficiency improvement (Tol and Madessa, 2025). Within a circular assessment approach, these findings suggest that efficiency metrics should include indicators related to return temperature and ΔT ,

as they represent direct levers for reducing wastage and increasing resource utilization. Importantly, these indicators are interpretable to operators and can be connected to specific intervention types (substation control tuning, balancing, retrofits, or consumer guidance), making them well suited for a closed-loop monitoring framework.

At the network level, Stock et al. (2024) address the optimization of DH network separation to improve the utilization of heat-source potentials, particularly when temperature levels are mismatched or source availability is unfavourable (Stock et al., 2024). This is directly connected to circular efficiency because separation and reconfiguration can enable local use of waste heat or low-temperature sources, reduce transport losses, and better align system temperature with source temperature. From a planning perspective, Vesterlund and Toffolo (2017) examine optimization of DH network expansion by balancing capital costs of piping against pumping costs (Vesterlund and Toffolo, 2017), which is relevant to assessment because it supports evaluation of the long-term effects of infrastructure decisions on resource-efficiency indicators (losses, pumping energy, and source availability). These planning and topology decisions also motivate why operational assessment must be regime-aware: what is “efficient” during peak winter operation may differ from shoulder seasons, when low-temperature sources or local separation strategies become more advantageous.

Finally, recent applied studies support the feasibility and relevance of operator-oriented data-driven assessment. Tasić et al. (2024) compare machine-learning approaches for DH load prediction, providing evidence that practical predictive baselines can be built and evaluated in DH contexts (Tasić et al., 2024). Tasić et al. (2025) analyse the effect of sliding-window techniques on decision-tree time-series forecasting, which is directly relevant to real operational data where regime changes and temporal context strongly affect model performance (Tasić et al., 2025). Tasić et al. (2025b) further position irregular time series and explainability as central themes for industrially relevant energy modelling (Tasić et al., 2025b). Collectively, these studies motivate the present work’s emphasis on a closed-loop-inspired workflow: not only producing forecasts but using them to construct interpretable loss signatures and a feedback mechanism that supports systematic intervention design and evaluation over time.

In summary, the literature provides strong individual components - forecasting, explainability, optimization/control, consumer-side modelling, and adaptive learning - but the operational gap remains the integration of these components into a transparent, measurable loop for continuous circular-efficiency improvement. The framework developed in this paper addresses this gap by explicitly linking baseline modelling with KPI/EEI wastage signatures and explainable attribution, thereby enabling intervention selection and post-intervention assessment in a form that can be communicated to operators and aligned with end-user-oriented objectives.

Methodology

This paper addresses the assessment of circular energy efficiency based on real operational data collected from the SCADA system of the Faculty of Mechanical Engineering in Nis, with a focus on the district heating substation - lamella L17. The analysis relies on time-synchronized measurements including outdoor air temperature, secondary-side supply water temperature, and a signal of delivered thermal power, from which the consumed thermal

energy per time step is calculated. The dataset represents an authentic record of system operation under real exploitation conditions and inherently contains nonlinearities, delays, and regime changes characteristic of practical district heating systems.

The primary objective of the study is not limited to energy consumption forecasting, but rather to the definition of a reliable baseline representation of system behaviour. This baseline describes the expected energy consumption under given external and temporal conditions and serves as a reference for further efficiency analysis. Accordingly, energy consumption is modelled as a time-series regression function of outdoor temperature, secondary-side-supply temperature, and temporal features describing time of day and day of week. To capture the dynamic nature and thermal inertia of the system, lagged values of previously consumed energy are also included in the model.

Based on this set of input variables, ensemble machine learning models are trained, with preference given to models that demonstrate the best generalization performance on a test set obtained through chronological data splitting. The selected model is not interpreted as a physical representation of the system, but as a statistically learned approximation of the normal, expected operating regime of the L17 substation. In this sense, the model output is treated as a reference baseline prediction.

Model validation is performed using standard regression metrics. The primary evaluation metric is the Root Mean Squared Error (RMSE),

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (E_i - \hat{E}_i)^2},$$

which emphasizes larger deviations and enables the identification of operating regimes with potentially significant energy excess. In addition, the Mean Absolute Error (MAE),

$$MAE = \frac{1}{N} \sum_{i=1}^N |E_i - \hat{E}_i|,$$

and the coefficient of determination R^2 ,

$$R^2 = 1 - \frac{\sum (E_i - \hat{E}_i)^2}{\sum (E_i - \bar{E})^2},$$

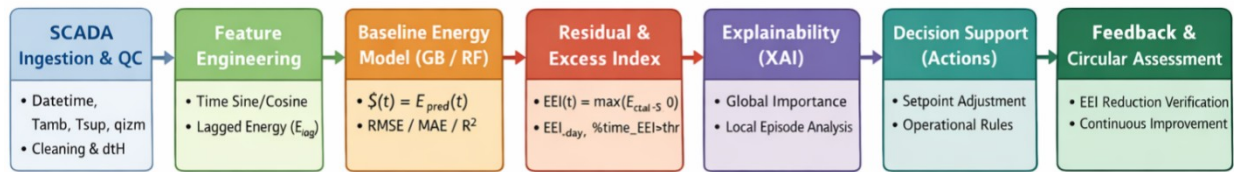
are used to assess overall prediction accuracy and the proportion of variance in measured energy consumption explained by the model. The difference between measured and predicted energy consumption is interpreted as an indicator of deviation from expected system behaviour. Rather than being directly classified as a fault or loss, this deviation is treated as an analytical signal indicating potentially inefficient or atypical operating regimes. Emphasis is placed on positive deviations, where actual consumption exceeds the baseline prediction, as these cases represent relevant candidates for circular energy efficiency analysis.

To make such deviations interpretable and operationally meaningful, an explainability layer based on Explainable Artificial Intelligence (XAI) methods is introduced. At the global level, the relative contribution of individual input variables to the baseline model prediction is analysed to identify dominant drivers of energy consumption. At the local level, the analysis focuses on specific time instances with the largest deviations, examining how variations in

each input variable influence the model output. This enables interpretation of concrete operational situations associated with increased energy consumption.

The central scientific contribution of this work lies in the definition of a reliable baseline prediction and the application of explainable artificial intelligence for interpreting the learned system behaviour. Elements related to the assessment of circular energy efficiency and potential operational interventions are presented as guidelines derived from the analysis results and illustrated through the proposed block diagram, rather than as explicitly implemented control strategies.

Figure 1. Closed-loop SCADA - XAI for circular energy efficiency



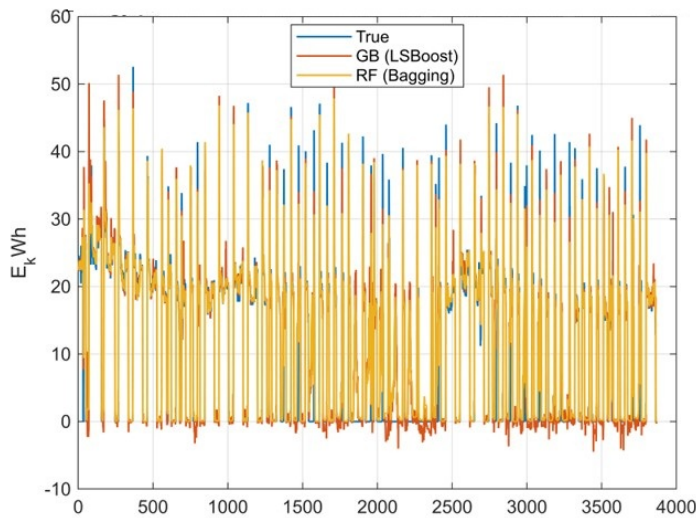
This approach enables flexible application of methodology in accordance with system-specific characteristics and operator requirements, without compromising the primary research objective.

In this way, a closed analytical loop is established in which real SCADA data are used to learn baseline system behaviour, identify deviations, and explain their underlying causes. The proposed approach demonstrates how modern machine learning and XAI techniques can support the assessment of circular energy efficiency in real district heating systems, as illustrated by the case study of the Lamella L17 substation at the Faculty of Mechanical Engineering in Nis.

Results and discussion

The presented results refer to the prediction of consumed thermal energy for the heating substation (lamella) L17, based on time-synchronized SCADA measurements. In total, 12,894 valid samples were used, and the dataset was chronologically split into 9,025 samples for training (TRAIN) and 3,869 samples for testing (TEST). The typical sampling interval is approximately 0.250 h (about 15 minutes), and a maximum historical lag of 4 was introduced, meaning that the input feature set includes previous signal values up to four - time steps back.

Two machine learning models were compared: (1) Least-Squares Boosting (LSBoost) and (2) Random Forest in a bagging regime (RF). For Least-Squares Boosting, hyperparameters were tuned on a meta-validation set, yielding the following best configuration: cycles = 300, learning rate = 0.200, maxSplits = 10, minLeaf = 10, with RMSE(meta) = 2.6693. Subsequently, an RF model was trained as a “baseline” for comparison.

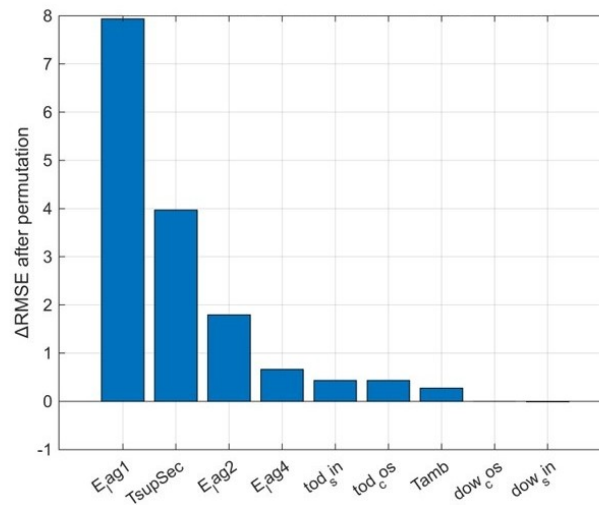
Figure 2. Comparative overview of model performance on the test set

From the energy prediction plot (Fig.2) on the test set, it can be observed that both models follow the overall level of the signal; however, RF behaves more robustly in segments where pronounced peaks and rapid changes occur (which is typical for energy values computed over discrete sampling intervals). This suggests that the bagging ensemble smooths noise and local anomalies more effectively, whereas boosting may be more sensitive to specific training patterns in the presence of abrupt spikes.

Table 1. Numerical comparison of model performance (RF vs. LSBoost): RMSE, MAE, and R^2

MODELS	RMSE	MAE	R^2	BEST RMSE	BEST MAE	BEST R^2
RF	3.8537	1.6696	0.89446	3.8537	1.6696	0.89446
LSBOOST	4.0364	1.8435	0.88422			

The numerical evaluation on the TEST split, which is presented in Table 1, confirms the advantage of the Random Forest model. In practical terms, the obtained $R^2 \approx 0.895$ indicates that the model explains approximately 89-90% of the variance of the target variable on the test set, which is a very solid level of accuracy for real operational data that contain noise, regime changes, and potential measurement errors. The difference between RMSE and MAE is expected: RMSE is higher because it penalizes larger errors (e.g., peaks) more strongly, whereas MAE better reflects the typical absolute error in day-to-day operation. In addition to predictive accuracy, model interpretation was performed using permutation importance on the test set.

Figure 3. XAI analysis of predictor importance: permutation test and change in model error

In the feature-importance histogram (Fig. 3), the dominant predictors are the thermal energy consumption lagged by one time step, followed by the secondary-side supply water temperature, then the thermal energy consumption lagged by two time steps and the thermal energy consumption lagged by four time steps, while the time-of-day components (sine and cosine) and the outdoor air temperature are notably smaller but still measurably relevant; the day-of-week components (sine and cosine) are almost negligible. This ranking is consistent with energy time-series behaviour: autoregressive features typically carry the most information (energy in the next step is strongly related to energy in previous steps), while the secondary-side supply temperature represents a direct operational “signature” of heat delivery (secondary supply temperature is closely linked to thermal load). The smaller contribution of the outdoor temperature and time-of-day components indicates that part of the meteorological and scheduling influence is already captured through the recent consumption history (lags), yet additional information from the daily cycle and ambient conditions remains beneficial.

Overall, the results show that, for L17 under the observed conditions, RF is a more reliable choice than LSBoost: it yields higher accuracy (lower RMSE and MAE, higher R^2) and tracks varying operating regimes more stably.

The XAI analysis further confirms that consumption dynamics are primarily driven by the system’s short-term inertia and by the operational state of the secondary circuit, which is valuable for operators because it highlights which variables should be prioritized when interpreting deviations and potential losses. In this section, it is important to emphasize the connection between the obtained results and the last two blocks of the block diagram presented in the previous section - Decision Support (Actions) and Feedback & Circular Assessment - in order to complete the closed-loop logic of circular energy efficiency. Within the *Decision Support (Actions)* block, results derived from the baseline predictive model, residual/EEI indicators, and XAI analyses will be translated into a set of practical operational guidelines and decision rules. The goal is for elevated EEI episodes not to be treated merely as “statistical deviations,” but as clear indicators of potentially suboptimal operating regimes. In this sense, future work will define procedures for identifying typical patterns (e.g., frequent EEI episodes in specific time windows, associations between EEI and secondary-side

operating temperatures, or sudden localized deviations), followed by corresponding interventions (setpoint correction, heating-curve adjustment, night-regime optimization, verification of sensors and actuators, etc.). This ensures that the analytical layer (ML + KPI + XAI) gains direct operational applicability in control and monitoring.

The *Feedback & Circular Assessment* block represents the final step that closes the loop and completes the concept of circular efficiency. After interventions are implemented, a repeated evaluation using the same KPI/EEI metrics and comparison against the baseline will be performed to quantitatively confirm that “excess” consumption (wastage) has been reduced and that the operating regime has stabilized. This feedback mechanism enables iterative improvement: interventions are not treated as one-off actions, but are verified, adjusted, and systematically refined through continuous monitoring. In this way, future research will enable full closed-loop realization: prediction - wastage detection (EEI) - explanation (XAI) - operational action - effect verification, thereby completing, both methodologically and practically, the assessment and enhancement of circular energy efficiency.

Conclusions

This study advances a practical pathway for operationalizing *circular energy efficiency* in district heating by treating circularity not as an abstract sustainability principle, but as a measurable, continuously assessable property of real system operation.

The core contribution is the establishment of a data-driven baseline learned from time-synchronized SCADA measurements for the Lamella L17 substation, which represents “expected” behaviour under prevailing external and temporal conditions, rather than a physics-based surrogate. This baseline framing is essential because it enables the separation of routine variability from potentially avoidable excess, and it provides a consistent reference against which circular-efficiency deviations can be monitored in a repeatable manner. Beyond baseline forecasting, the work strengthens the bridge from predictive analytics to circular-efficiency assessment by interpreting prediction deviations as an analytical signal for atypical or potentially inefficient regimes - specifically focusing on *positive deviations* where measured consumption exceeds the baseline estimate. This perspective is important for operational environments: deviations are not automatically treated as “faults,” but as *structured indicators* that can trigger targeted diagnostic steps. In this way, the baseline model becomes a scalable screening mechanism for identifying candidate episodes of resource dissipation (e.g., oversupply behaviour, transient anomalies, or control-driven mismatches) that merit deeper inspection.

Interpretability is addressed through an explicit explainability layer that supports operational trust and actionability. By combining global and local explainability analyses, the paper demonstrates how the learned baseline can be *explained* in terms of dominant drivers, and how high-deviation instances can be examined in a structured manner to connect operational context to observed excess. This is a key element for circular-efficiency assessment because it transforms model output from a “black-box prediction” into an evidence-based diagnostic tool that can be communicated to practitioners and used for prioritization.

At the same time, the paper deliberately positions the intervention layer as a *forward-looking operationalization*, not as a fully implemented control strategy. The block-diagram logic clarifies how the analytics stack (baseline + deviation indicator + explainability) can feed into decision support and subsequent verification, while remaining adaptable to site-specific constraints and operator requirements.

This is aligned with ECO4ALL’s emphasis on linking efficiency metrics to consumer-relevant outcomes: a transparent monitoring and diagnostic process is a prerequisite for fairer heat delivery, reduced overheating/underheating risk, and more accountable operation—benefits that directly affect end-user comfort and costs.

Several limitations define the next research steps. First, the analysis is currently centered on a single substation and a particular operational context; expanding to multiple substations and seasons would strengthen external validity and enable comparative circular-efficiency benchmarking. Second, the present feature set focuses on readily available SCADA signals; incorporating additional hydraulic and temperature-performance indicators (e.g., return temperature behaviour, ΔT signatures, and flow-related proxies where available) would provide a richer mapping between deviations and physically meaningful loss mechanisms. Third, operational deployment requires explicit governance of data quality (sensor drift, missingness, and regime labelling), as well as clear thresholds for actionable alerts versus benign variance.

Future work will therefore focus on completing the closed-loop circular assessment: translating explainability-guided deviation patterns into formalized operational playbooks (Decision Support) and then verifying the effectiveness of interventions through repeated KPI/EEI evaluation (Feedback & Circular Assessment).

This progression - baseline prediction which include wastage detection, explainability, action and verification provide a concrete, scalable mechanism for continuous improvement and for demonstrating, with operational evidence, that circular-efficiency measures yield measurable benefits for system performance and end users.

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CIRCULAR BIOECONOMY APPLICATIONS FOR SUSTAINABLE BIOMASS MANAGEMENT SUPPORTING THE GREEN TRANSITION IN INSULAR REGIONS

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Abstract

Insular regions face challenges such as energy deficit, a declining agricultural sector, deteriorating water and soil quality, a rise in the risk of natural disasters brought on by climate change, coastal pollution, ineffective biowaste management, deteriorating ecosystems, a loss of biodiversity, etc. Circular and resource-efficient economic models, which consider the entire material cycle to promote reuse as well as waste reduction and efficient resource utilization, are increasingly replacing linear economic models based on production-consumption-disposal systems. A bioeconomy covers a wide range of sectors and systems which are based on biological resources (animals, plants, microorganisms, and biomass, including organic waste), their functions and principles. The transition to circular bioeconomy will be further reinforced through the development and uptake of innovative technologies as well as the training of scientists and researchers through the collaborative ecosystem at national and international level.

This paper presents the research infrastructure and two selected representative case studies developed within the framework of the Center for Sustainable and Circular Bioeconomy of the University of the Aegean (Aegean_BIOECONOMY).

*The first case study investigates the cultivation of *Arthrospira* (*Spirulina*) *platensis* on diluted, non-sterile cheese whey, evaluating the effects of substrate concentration, pH and illumination on biomass production and nutrient consumption. The results show that alkaline conditions and light/dark photoperiods significantly enhance biomass productivity, while achieving high removal efficiencies for organic matter and nutrients, highlighting the feasibility of simultaneous wastewater treatment and biomass production. The second case study examines the production of bioplastics (polyhydroxyalkanoates - PHAs) using mixed microbial cultures under long-cycle feast-famine operation. Effective enrichment of PHA-storing microorganisms and substantial intracellular polymer accumulation were achieved, despite operational challenges related to sludge viscosity and aeration.*

Overall, the findings demonstrate that biological valorization pathways can convert locally agro-industrial streams into value-added bioproducts, supporting resource efficiency, waste reduction and regional resilience. The study underscores the role of dedicated research infrastructures in enabling circular bioeconomy solutions tailored to insular environments and provides a transferable framework for sustainable regional development aligned with European bioeconomy and climate objectives.

Key words: Circular bioeconomy, island sustainability, research infrastructure, green transition, agro-industrial waste, bioplastics, cyanobacteria

Introduction

The transition to a circular bioeconomy is essential for achieving sustainability, environmental protection, and economic modernization in regions that are highly dependent on natural resources and ecosystem services. Bioeconomy encompasses all sectors that rely on biological resources (biomass, organic waste, organisms) and integrates land, marine ecosystems, primary production sectors (agriculture, forestry, fisheries, aquaculture) and industrial applications for food, materials, and energy production. Embedding circularity and sustainability within this framework aligns renewable biological resource utilization with environmental, economic, and societal objectives (EC, 2020; UN, 2020).

In a linear economy, as it is in most European insular regions the current situation, materials are taken from the Earth to be used in product making and are eventually thrown away as waste. In the case of circular economy, by contrast, waste is not being produced in the first place. The circular economy is a system where materials never become waste and nature is regenerated. Products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. A circular system can help in tackling climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources. The three basic principles driven by design are eliminating waste and pollution, circulating products and materials at their highest value, and regenerating nature and are visually represented by the butterfly diagram (<https://www.ellenmacarthurfoundation.org/>), (Figure 1).

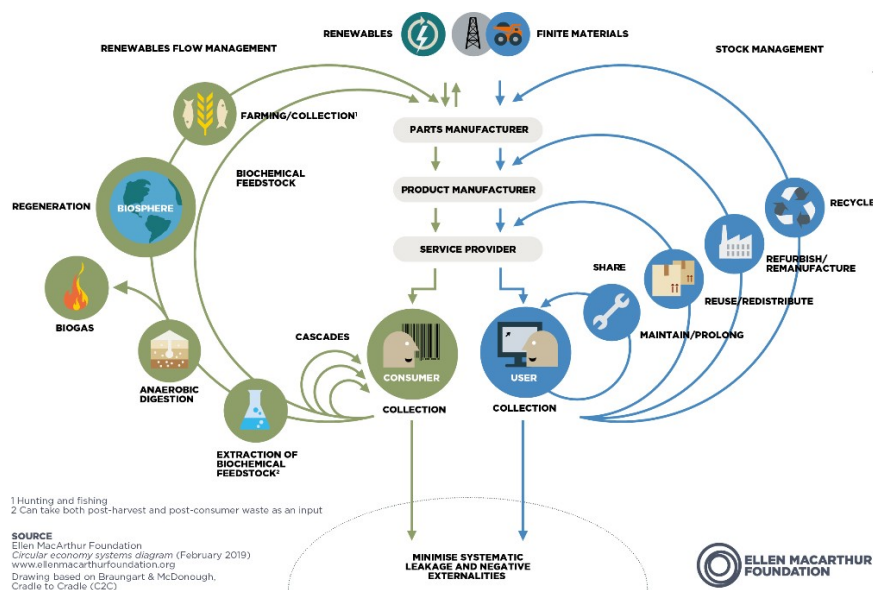


Figure 1. Visualising circular economy (the butterfly diagram)

The current research is focused on the biological cycle — recovering, treating, and valorizing bio-resources in ways that reduce pressure on ecosystems and promote sustainability. In islands, where resource limitations and waste management challenges are significant, circularity is not only environmentally beneficial but also economically strategic. Insular regions face distinctive challenges — limited land area, resource scarcity, seasonal tourism pressures, and logistical constraints — which require tailored solutions for sustainable development. In Greece, the Aegean islands represent a cluster of such regions where circular bioeconomy concepts can drive the green transition by enhancing resource efficiency, supporting ecosystem services, and creating sustainable employment opportunities. All these, make them ideal testbeds for circular solutions.

Research and innovation initiatives have increasingly focused on circular bioeconomy solutions tailored to local environmental and socio-economic conditions. This paper provides a general description of the integrated research activities and innovative applications developed by the Center for Sustainable and Circular Bioeconomy of the University of the Aegean, highlighting their contribution to the green transition of insular areas.

Selected case studies and research results are presented related to the sustainable production and management of biomass, which is considered particularly important for the islands of the North Aegean Region where the primary/agri-food sector is the key pillar of economic development. Olive oil, cheese, wine, milk, as well as other products complete the basket of famous products of the region, due to the combination of the special geoclimatic conditions of the Northern Aegean region and the traditional production practices – similar to other regions in the Mediterranean. During production and processing, significant amounts of by-products and residues - biowaste - are produced. The management of waste from olive mills, cheese factories and wineries, slaughterhouse residues, livestock waste and residues from fruit processing is a major environmental as well as economic problem for businesses. The seasonal variation and the special characteristics of these by-products make it even more difficult to find sustainable and efficient management solutions.

The agri-food sector is a major contributor to organic waste generation, with the dairy industry producing large volumes by products such as cheese whey, which is characterized by high concentrations of biodegradable organic matter, as well as significant levels of nitrogen and phosphorus (Yadav et al., 2015; Zandona et al., 2021). When improperly managed, cheese whey disposal can lead to severe environmental pollution, particularly in aquatic ecosystems, due to oxygen depletion and eutrophication (Lucakova, 2022). Despite the development of several valorization pathways, including protein recovery and fermentation processes, sustainable and economically viable whey management remains a challenge, especially for small- and medium-scale dairies and geographically constrained regions such as islands (Kalantzis et al., 2023; Nazos et al., 2023).

Microalgae and cyanobacteria cultivation has emerged as a promising strategy for the integrated treatment and valorization of nutrient-rich wastewaters. These microorganisms can assimilate inorganic and organic nutrients while producing biomass rich in proteins, pigments, lipids and bioactive compounds (Koller et al., 2014; Calicioglu & Demirer, 2022). Among them, *Arthrospira* (*Spirulina*) *platensis* is of particular interest due to its high growth rates, tolerance to alkaline conditions and ability to outcompete contaminating microorganisms under elevated pH and salinity (Sukenik et al., 2009; Delrue et al., 2017). These characteristics make *A. platensis* especially suitable for cultivation on non-sterile waste-derived substrates, thereby reducing operational complexity and production costs.

Agro-industrial waste and residues can also be valorized to meet the sustainable consumption goals, through their conversion to bioplastics. The extensive use of conventional,

fossil-based plastics has generated severe environmental challenges, including persistent pollution, microplastic accumulation and increasing greenhouse gas emissions associated with their production and disposal. A significant share of global plastic production is linked to short-lived applications, particularly packaging, which rapidly become waste and intensify environmental pressures (Ellen MacArthur Foundation, 2022). In response, biodegradable and bio-based alternatives have gained increasing attention as part of circular bioeconomy strategies aimed at decoupling material production from fossil resources. Among bioplastics, polyhydroxyalkanoates (PHAs) are considered especially promising due to their complete biodegradability in natural environments, favorable thermoplastic properties and wide range of applications (Koller et al., 2014). PHAs are intracellular polyesters synthesized by microorganisms as storage compounds, typically under conditions of excess carbon and limitation of essential nutrients such as nitrogen or phosphorus.

In this paper, information and results on the application of innovative solutions for the valorisation of agro-industrial waste and residues are presented as case studies and specifically:

- The evaluation of *Arthrospira* (Spirulina) *platensis* growth on cheese whey
- The investigation of the production Polyhydroxyalkanoate (PHA) bioplastics of consistent composition from organic waste

Research Infrastructure and methodological framework

Mission and Objectives

The Center for Sustainable Circular Bioeconomy and Energy (Aegean_BIOECONOMY) is a multi-disciplinary research infrastructure hosted by the University of the Aegean (Department of Environment) aimed at supporting the transition from a linear to a circular bioeconomy in the insular regions of the North and South Aegean (Greece). It was established within the framework of the action “Reinforcement of the Research and Innovation Infrastructure”, co-financed by Greece and the European Union through the European Regional Development Fund. The project had a total budget of approximately €1.37 million and a duration of 30 months, completed in October 2023.

The Center supports applied research, pilot-scale experimentation, and technology demonstration. The methodological framework combines field surveys, laboratory experiments, pilot-scale systems, material flow analysis, and environmental performance assessment tools. Emphasis is placed on the integration of scientific research with regional development priorities.

Aegean_BIOECONOMY provides a collaborative platform for research, technological innovation, education, and regional planning aligned with environmental legislation and sustainability goals. It bridges academic research with applied solutions that foster economic resilience, job creation, and sustainable development in island economies. The overall objective is the adoption of the EU Bioeconomy Strategy making sure it reflects the specific conditions of the island regions. This can lead to new jobs, contribution to achieve carbon neutrality, shift to the circular economy model, harnessing of healthy natural ecosystem as well as modernisation and strengthening industry.

Research areas

Aegean_BIOECONOMY is organized into four interlinked research themes that address priority needs for circular bioeconomy implementation in insular contexts. It is important to highlight that a core output of the project was the development of permanent research infrastructure — digital platforms, pilot-scale units, and laboratory tools that enable continuous experimentation and support collaboration with regional stakeholders. The research areas are categorized as:

- BIOMass — Sustainable Production and Management of Biomass
- Nature4Water — Sustainable Water and Soil Management
- REproduct — Recycling and Creation of New Materials
- Hotel Footprinting — Tourism Environmental Footprint Reduction

Regional engagement and stakeholder integration

Aegean_BIOECONOMY engages regional and local stakeholders — including SMEs, policymakers, community organizations, and tourism operators — to foster knowledge exchange and co-creation of sustainable solutions. Training programs, workshops, and events (e.g., spring schools on circular bioeconomy) enhance regional capacity and encourage adoption of innovative practices.

Selected case studies for the sustainable management of biomass

Arthrospira (Spirulina) platensis cultivation using cheese whey

Introduction and scope of the study

Biological processes, and especially biotechnology-based solutions, play a central role in the transition to circular economy by enabling the conversion of organic residues into high-value products while reducing environmental impacts (Vaitsis et al., 2022).

Previous studies have demonstrated the feasibility of cultivating *A. platensis* under mixotrophic conditions using dairy effluents, highlighting the potential for simultaneous biomass production and wastewater treatment (Pereira et al., 2019; Papadopoulos et al., 2022). However, important knowledge gaps remain regarding the influence of operational parameters such as substrate concentration, pH and illumination regime on biomass productivity and nutrient removal efficiency. Moreover, many existing studies rely on sterilized or extensively pretreated waste streams, limiting their applicability to real-world circular economy implementations. Addressing these gaps is essential for advancing *Arthrospira*-based systems from laboratory-scale investigations toward practical, sustainable applications.

The present study evaluates the cultivation of *Arthrospira* (*Spirulina*) *platensis* strain PCC8005 using diluted, non-sterile cheese whey as a nutrient source, aiming to partially substitute conventional synthetic growth media. Batch experiments were conducted to investigate the combined effects of cheese whey concentration, pH and illumination regime on biomass production, nutrient uptake and organic matter removal.

Specifically, the objectives were to assess the growth performance of *A. platensis* in whey-based media under alkaline conditions and compare biomass productivity under continuous illumination and light/dark photoperiods. The removal of parameters such as

chemical oxygen demand, nitrogen and phosphorus was determined and the operational conditions that optimize both biomass yield and treatment efficiency were identified.

By focusing on non-aseptic conditions and minimal pre-treatment requirements, the study seeks to provide results that are directly transferable to low-cost, decentralized and regionally adapted applications.

This work contributes to circular economy principles by demonstrating a biological pathway for the simultaneous treatment and valorization of cheese whey, a major by-product of the dairy industry. The cultivation of *Arthrospira platensis* enables the recovery of nutrients and organic carbon from cheese whey and their conversion into valuable microbial biomass, effectively closing material loops within the agri-food system (Abreu et al., 2012; Lafarga et al., 2021).

The proposed approach supports circular economy objectives through:

- Resource recovery, by transforming nitrogen, phosphorus and organic carbon into biomass rather than disposing of them as waste;
- Waste reduction, achieved through high COD and nutrient removal efficiencies, mitigating the environmental footprint of dairy effluents;
- Economic sustainability, enabled by the use of non-sterile substrates and the inherent robustness of *A. platensis* under alkaline conditions;
- Value creation, as the produced biomass can serve as a feedstock for bioenergy, biofertilizers or other bioproducts, extending the value chain beyond wastewater treatment (Mitra & Mishra, 2019).

Overall, the findings support the integration of microalgal biotechnology into sustainable waste management strategies and reinforce the role of *Arthrospira platensis* cultivation as a viable circular economy solution for the dairy sector.

Materials and methods

Microorganism and maintenance conditions

The cyanobacterium *Arthrospira (Spirulina) platensis* strain PCC8005 (Institut Pasteur, France) was used in this study. Stock cultures were maintained at the Waste Management Laboratory of the University of the Aegean in Erlenmeyer flasks containing Cogne-modified Zarrouk medium (CMZM) (Cogne et al., 2003). Cultures were incubated at 28 °C under continuous illumination provided by an 8 W LED light source (680 lm).

The CMZM contained (g L⁻¹): NaCl (1.0), CaCl₂ (0.03), K₂SO₄ (1.0), MgSO₄·7H₂O (0.08), K₂HPO₄ (0.5), NaNO₃ (2.5), NaHCO₃ (10.5), Na₂CO₃ (7.6), EDTA (0.08) and FeSO₄·7H₂O (0.01). Trace elements were supplied according to Cogne et al. (2003). Cultures used as inoculum were harvested during the exponential growth phase.

Cheese whey origin and pretreatment

Cheese whey was obtained from a local dairy processing unit located on Lesbos Island (Greece). The physicochemical properties of the whey were characterized by high organic content and acidic pH, reflecting typical dairy by-product composition (pH equal to 3.62 and COD value of 62.334 mg/L). Whey samples were stored at -20 °C until use.

Prior to cultivation experiments, cheese whey was centrifuged at 1500 rpm for 15 min and subsequently filtered through 1 µm filters to remove coarse suspended solids. This mild pretreatment aimed to reduce turbidity and facilitate light penetration while maintaining the non-sterile nature of the substrate, as previously suggested by Pereira et al. (2019).

Experimental design and cultivation conditions

Batch experiments were conducted in 250 mL Erlenmeyer flasks containing 130 mL of growth medium. Cheese whey was diluted with tap water to final concentrations of 2.5%, 5% and 10% (v/v). A whey concentration of 20% (v/v) was initially tested but excluded due to growth inhibition, in agreement with previous findings (Pereira et al., 2019).

Each flask was inoculated with 20 mL of *A. platensis* culture. Cultivation was performed at 28 °C for 14 days under two illumination regimes: (i) continuous illumination using fluorescent lamps (OSRAM FQ 39 W/840 HO), and (ii) a 12 h light/12 h dark photoperiod. Experiments were carried out at pH values of 8.5, 9.5 and 10.5. All trials were performed in triplicate. Zarrouk medium cultures served as controls.

Analytical methods

Growth was monitored by measuring optical density at 750 nm every two days. Biomass concentration was quantified as volatile suspended solids (VSS). Samples were filtered through 1 µm glass fiber filters, dried at 105 °C for 24 h and weighed. Subsequently, filters were combusted at 550 °C for 30 min to determine volatile solids content.

Chemical oxygen demand (COD), total nitrogen (TN), nitrate nitrogen (NO_3^- -N) and phosphate (PO_4^{3-} -P) concentrations were determined spectrophotometrically using Hach standard test kits.

Results and Discussion

Acclimation to whey-based media

All cultures exhibited a short acclimation period during the first 24 h following inoculation, reflecting metabolic adjustment to the complex organic substrate. Similar acclimation behavior has been reported for cyanobacteria cultivated on waste-derived media (Abreu et al., 2012; Pereira et al., 2019).

Growth under continuous illumination

Biomass production under continuous illumination increased with both whey concentration and pH. The highest biomass yield ($0.76 \text{ g L}^{-1} \text{ VSS}$) was obtained at pH 9.5 using 10% (v/v) whey. Cultures maintained at pH 8.5 exhibited significantly lower growth, confirming the preference of *A. platensis* for alkaline environments (Ogbonda et al., 2007; Papadopoulos et al., 2022).

Nitrogen uptake was enhanced at higher pH values, with maximum NO_3^- -N consumption observed at pH 10.5. Phosphate removal was nearly complete at lower whey concentrations, whereas partial removal was recorded at 10% (v/v), likely due to increased initial phosphorus loading.

COD removal exceeded 80% in most treatments, demonstrating effective organic matter utilization even in non-sterile conditions, consistent with previous studies on wastewater based *Arthrospira* cultivation (Calicioglu & Demirer, 2022).

Growth under light/dark cycles

Cultivation under a 12 h light/dark regime resulted in superior biomass production compared to continuous illumination. The highest biomass concentration of the study ($\approx 1.04 \text{ g L}^{-1} \text{ VSS}$) was achieved at pH 10.5 with 10% (v/v) whey. Enhanced growth under photoperiodic illumination has been attributed to improved photosynthetic efficiency and reduced photoinhibition (Marquez et al., 1993; Chen & Zhang, 1997).

Nitrogen removal under light/dark conditions was more pronounced, with near-complete nitrate depletion observed at pH 10.5. COD removal reached up to 85%, confirming the dual function of *A. platensis* cultivation as biomass production and wastewater treatment.

Table 1: Consumption of nutrients, COD removal and determination of VSS, during *Arthrospira platensis* growth using cheese whey. Cultures with continuous illumination and dark/light cycles. Values presented were measured in the first and last day of the trials

	Cheese Whey Concentration % (v/v)	Continuous illumination						Light/dark cycles			
		Experiment 1 pH=8.5		Experiment 2 pH=9.5		Experiment 3 pH=10.5		Experiment 4 pH=8.5		Experiment 5 pH=10.5	
TN (mg/L)		t0	t14	t0	t14	t0	t14	t0	t14	t0	t14
	2.50%	84	69	86	39	86	38	84	22	86	30
	5%	101	82	106	63	106	46	101	37	106	40
	10%	238	119	130	92	130	90	157	62	130	55
NO ₃ ⁻ N (mg/L)											
	2.50%	55	42	50	29	50	22	55	17	50	0.6
	5%	57	23	55	24	55	20	57	13	55	0.8
	10%	65	34	61	16	61	20	65	0.7	61	0.7
COD (mg/L)											
	2.50%	1135	0	1000	0	1000	0	1135	0	1000	63
	5%	1860	364	1580	221	1580	149	1860	85	1580	248
	10%	5210	974	4080	986	4080	973	5210	117	4080	535
PO ₄ ³⁻ (mg/L)											
	2.50%	6.1	<2	6.4	<2	6.4	<2	11.5	13.7	6.4	6.9
	5%	11.2	<2	11	<2	11.0	<2	14.0	14.7	11.0	11.4
	10%	23.8	19.7	28	17.9	28.0	17	23.8	20.2	28.0	18.1
VSS (g/L)											
	2.50%	0.16	0.18	0.16	0.33	0.16	0.29	0.12	0.60	0.12	0.74
	5%	0.16	0.22	0.16	0.46	0.16	0.50	0.11	0.63	0.11	0.97
	10%	0.12	0.28	0.12	0.76	0.12	0.71	0.14	0.65	0.14	1.04

Comparative assessment

Light/dark cycles combined with alkaline pH conditions favored biomass productivity and nutrient uptake. Even at low whey concentrations, photoperiodic illumination outperformed continuous lighting. These findings support the feasibility of integrating *A. platensis* cultivation into circular economy schemes for dairy wastewater valorization (Vaitis et al., 2022). In Table 1, the consumption of nutrients, COD removal and determination of VSS in cultures with continuous illumination and dark/light cycles are presented.

The investigation of the production of Polyhydroxyalkanoate (PHA) bioplastics of consistent composition using organic waste

The use of organic waste streams as feedstocks for PHA production represents a key pathway toward sustainable and economically viable bioplastics. Organic waste and waste-derived volatile fatty acids provide low-cost carbon sources while simultaneously addressing waste management challenges, thereby aligning PHA production with circular bioeconomy principles (Ntaikou et al., 2014). In this context, mixed microbial cultures (MMCs) offer significant advantages over pure cultures, as they can operate under non-sterile conditions and tolerate variable substrate compositions, reducing operational complexity and costs (Serafim et al., 2008; Kourmentza et al., 2017). Feast–famine operational strategies selectively enrich PHA-accumulating microorganisms, enhancing process robustness and storage capacity. Overall, bioplastics production from organic waste supports sustainable biomass management by converting residual carbon into value-added materials, contributing to waste reduction,

material circularity and climate mitigation—benefits that are particularly relevant for insular and resource-constrained regions supporting the green transition.

Mixed Microbial Cultures (MMCs) have been tested extensively to produce PHAs due to their potential in reducing costs both by utilizing organic waste as feedstock and by minimizing aseptic conditions. Replacing single-use petrochemical plastics with materials manufactured using organic wastes could be a significant step in the advancement of circular economy. Optimization of MMC enrichment in PHA producing microorganisms is crucial for the maximization of PHA production.

The use of MMCs can reduce the production costs as aseptic conditions are not required for the whole process. A simplified method of producing PHA bioplastics from synthetic medium and organic waste, is developed to be able to qualitatively test parameters that control the composition of PHA bioplastics and the productivity of the process.

Materials and Methods

Inoculum and reactor setup

Draw-fill reactors were used using 3.5 days cycles and Sludge Retention Time (SRT) of 7 days to simplify the enrichment procedure. The biomass was enriched with microorganisms in concentrations of 50 and 83 mmol/day. Growth conditions with and without aeration were tested. Accumulation of PHA bioplastics was also carried out using Draw-and-Fill reactors (DFR) with the enriched biomass to obtain product above 40% by weight of cell mass. The production was validated gravimetrically and qualitatively with Nile Red microscopy. Extraction with chloroform was performed to obtain films. COD, VFA and ammonia measurements were performed to elucidate the process. Biomass growth in concentrations over 2.5 was achieved using 83 Cmmol/day, while growth using 50 Cmmol/day was insignificant. Aeration was found to be imperative for growth.

Feeding regime and operational strategy

The enrichment strategy was based on long operational cycles (two cycles per week) and alternating feast–famine conditions. At the start of each cycle, the reactor was fed with a synthetic medium containing acetate and propionate as volatile fatty acid (VFA) carbon sources and ammonia as the nitrogen source.

The point of this long-cycle method is to produce PHAs viably without automatic feed systems. The method relies on alternating periods of feast and famine. A DFR, (draw and fill reactor - Figure 2) was used to feed activated sludge with Volatile Fatty Acids (VFAs) in this case mixtures of acetate and propionate as a source of Carbon and ammonia as a source of nitrogen in the beginning of the cycle. A famine period of at least 5 times the feast period favors the growth of Mixed Microbial Cultures (MMCs) able to store PHA granules as a source of carbon (Figure 3).



Figure 2. Draw and Fill reactor used

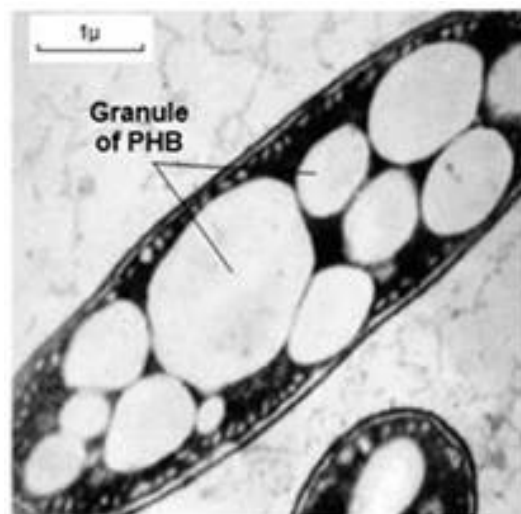


Figure 3. Transmission electron micrograph of granules of PHB in microorganisms (Lenz and Marchessault 2005)

Organic loading rates (OLR) of 42.9 and 71.4 Cmmol d⁻¹ were applied to assess their influence on microbial enrichment and system performance. Famine periods were maintained at least five times longer than feast periods, favoring microorganisms capable of intracellular PHA storage (Bengtsson et al., 2017).

Monitoring and accumulation experiments

Biomass evolution during enrichment was monitored by measuring volatile suspended solids (VSS). Following selected enrichment cycles, accumulation experiments were conducted by supplying carbon without nitrogen, thereby suppressing biomass growth and promoting PHA storage.

Chemical oxygen demand (COD) and ammonia concentrations were measured to confirm substrate consumption and nutrient limitation. During accumulation phases, increases in VSS were assumed to be predominantly associated with intracellular PHA accumulation.

Results and Discussion

Enrichment performance at low organic loading

At an OLR of 42.9 Cmmol d⁻¹, microbial growth peaked approximately 1.5 days into the cycle. Prolonged aeration resulted in increased medium viscosity and slime formation, which impeded oxygen transfer. Such behavior is commonly associated with nitrogen limitation and extracellular polymeric substance (EPS) production (Silva et al., 2017).

Effect of increased organic loading

Increasing the OLR to 71.4 Cmmol d⁻¹ delayed the growth peak, indicating improved substrate availability. However, slime formation and aeration limitations persisted, suggesting that long-cycle operation under nitrogen-limited conditions inherently promotes EPS production.

PHA accumulation potential

After eight enrichment cycles at the higher OLR, accumulation experiments demonstrated significant polymer storage. VSS increased by 39.7% after 23 h and by 47% after 32 h, indicating effective PHA accumulation. These results confirm that the enriched MMCs were capable of storing carbon intracellularly when growth was restricted. VSS monitoring in the enrichment phase and in the production stage is presented in Figures 4a and 4b.

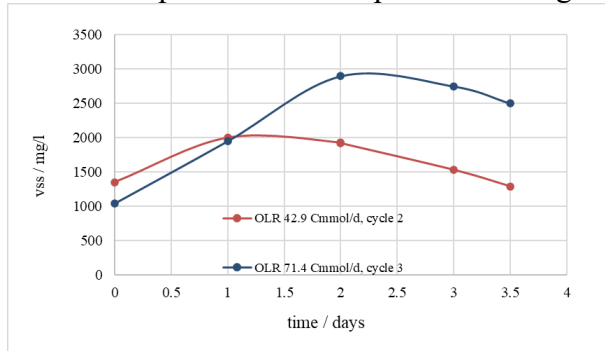


Figure 4a. VSS monitoring in the enrichment stage

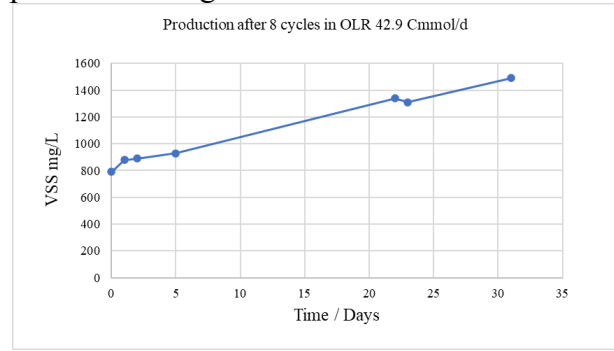


Figure 4b. VSS monitoring in the production stage

Substrate utilization dynamics

COD and ammonia were rapidly depleted within the first day of the cycle at lower OLR, confirming the establishment of clear feast–famine conditions. Rapid nitrogen depletion likely contributed both to PHA accumulation and EPS release, highlighting the need for careful nutrient management in long-cycle systems.

Process implications

The results demonstrate that PHA production using long-cycle operation is feasible without automated feeding. However, excessive slime formation presents a critical operational challenge. Future optimization should focus on shorter cycles, improved nutrient control and gradual transition to real organic waste streams, in line with circular bioeconomy principles (Ntaikou et al., 2018; Bengtsson et al., 2017).

Conclusions

The Center for Sustainable Circular Bioeconomy and Energy represents a model of how research infrastructures can catalyse transition to a circular bioeconomy in insular and geographically dispersed regions. By bridging multidisciplinary science, stakeholder engagement, and applied innovation, it contributes to sustainable development aligned with global and European green transition agendas.

The study demonstrates that circular bioeconomy strategies can effectively support the green transition of insular regions. By integrating biomass valorization, renewable energy production, nature-based solutions, material recovery, and environmental footprint assessment, island territories can enhance resource efficiency while protecting fragile ecosystems. The presented approach provides a replicable model for other insular and remote regions pursuing sustainable development pathways.

This study demonstrates the pivotal role that targeted research infrastructures can play in accelerating the transition toward a circular bioeconomy in insular and resource-constrained regions. Through the activities of the Center for Sustainable Circular Bioeconomy and Energy (Aegean_BIOECONOMY), an integrated framework was developed that combines applied research, pilot-scale experimentation and stakeholder engagement to address critical

challenges related to biomass management, waste valorization and environmental sustainability.

The selected case studies highlight the feasibility and effectiveness of biological approaches for closing material loops within island agri-food systems. The cultivation of *Arthrospira* (*Spirulina*) *platensis* on cheese whey demonstrated that a problematic dairy by-product can be simultaneously treated and valorized under non-sterile conditions, achieving substantial biomass production and high removal efficiencies for organic matter and nutrients. The results confirm that alkaline pH and photoperiodic illumination enhance both biomass productivity and wastewater treatment performance, reinforcing the suitability of *A. platensis* for decentralized applications in island environments. This approach supports resource recovery, reduces environmental pressures associated with whey disposal and creates opportunities for value-added bioproducts.

In parallel, the investigation of polyhydroxyalkanoate (PHA) production using mixed microbial cultures illustrated the potential of converting organic carbon into biodegradable bioplastics through cost-efficient enrichment and accumulation strategies. Although operational challenges such as excessive slime formation were identified, the results confirmed that long-cycle feast–famine regimes can enrich PHA-storing microorganisms and achieve significant intracellular polymer accumulation. These findings underline the importance of operational optimization and nutrient management to improve process stability and scalability, particularly when transitioning from synthetic substrates to real organic waste streams.

Beyond the technical outcomes, the study emphasizes the broader contribution of circular bioeconomy interventions to regional development. By integrating biomass valorization, renewable materials production, nature-based solutions and environmental footprint assessment, the Aegean_BIOECONOMY initiative provides a replicable model for strengthening local value chains, reducing dependence on imported resources and enhancing environmental resilience in island territories. The engagement of regional stakeholders further supports knowledge transfer and facilitates the uptake of sustainable practices aligned with European Green Deal and bioeconomy strategies.

Overall, the results confirm that circular bioeconomy strategies, when supported by dedicated research infrastructures and region-specific implementation frameworks, can significantly contribute to the green transition of insular regions. Future efforts should focus on scaling up pilot applications, integrating multiple valorization pathways and strengthening policy–science–industry linkages to maximize environmental, economic and social benefits.

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CIRCULAR POLICY FRAMEWORK IN THE FOOD SECTOR FOR BRIDGING REGULATION BUSINESS PRACTICES AND CONSUMER PROTECTION IN THE REPUBLIC OF NORTH MACEDONIA

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Abstract

The transition towards a circular economy in the food sector of the Republic of North Macedonia requires a coherent policy framework capable of bridging regulatory requirements, business practices and consumer protection. This paper examines how existing regulatory instruments influence the adoption of circular strategies within agri-food companies, building upon prior national and regional research on circular economy models. Based on an empirical study conducted among food sector enterprises, the research explores the gap between regulatory knowledge and actual business practices, with particular emphasis on packaging eco-design, bio-waste management and the role of digital technologies. The analysis identifies key structural and economic barriers that hinder circular strategy adoption, while also examining the role of the business sector in informing consumers and strengthening transparency as an integral component of consumer protection. The findings provide policy-relevant insights for improving support mechanisms, enhancing regulatory coherence and facilitating the green transition of the agri-food sector in line with European Union standards and the Green Agenda for the Western Balkans.

Key words: circular economy, food sector, regulation, business practices, consumer protection, North Macedonia.

Introduction

The transition towards a circular economy (CE) has evolved from an environmental aspiration into an economic imperative for the agri-food sector in Southeast Europe. Under conditions of increasing resource scarcity, market volatility and environmental pressures, the traditional linear model of “take–make–dispose” is becoming economically and socially unsustainable, giving way to restorative systems that maximise resource efficiency and value retention (Pearce and Turner, 1990; Ghisellini et al., 2016).

For the Republic of North Macedonia, a developing economy and EU candidate country, this transition is closely linked to the implementation of the European Green Deal and the Green Agenda for the Western Balkans, as well as the Farm to Fork Strategy, which sets ambitious targets for waste reduction, sustainable packaging and food system transformation by 2030 (European Commission, 2020; Regional Cooperation Council, 2020). Previous national studies indicate that the agri-food sector holds significant potential for the adoption of circular practices, particularly in the management of by-products and waste streams (Бојковска К., 2021). However, a persistent gap remains between strategic policy objectives and the operational capacities of private sector actors.

The effectiveness of the circular transition largely depends on the interaction between three interrelated dimensions: regulatory frameworks, business practices and consumer protection. While regulatory instruments are expected to provide incentives and clear compliance mechanisms, businesses are required to invest in organisational and digital capacities that enable traceability, resource optimisation and transparency (Bote Alonso et al., 2022). At the same time, consumer protection in the context of circular economy extends beyond food safety, encompassing the right to accurate, transparent and verifiable information regarding the environmental footprint of food products.

Against this background, this paper aims to analyse how regulatory knowledge, economic constraints and digitalisation capacity influence circular strategy adoption in the Macedonian food sector, while also addressing the role of consumer information as a core component of circular policy design.

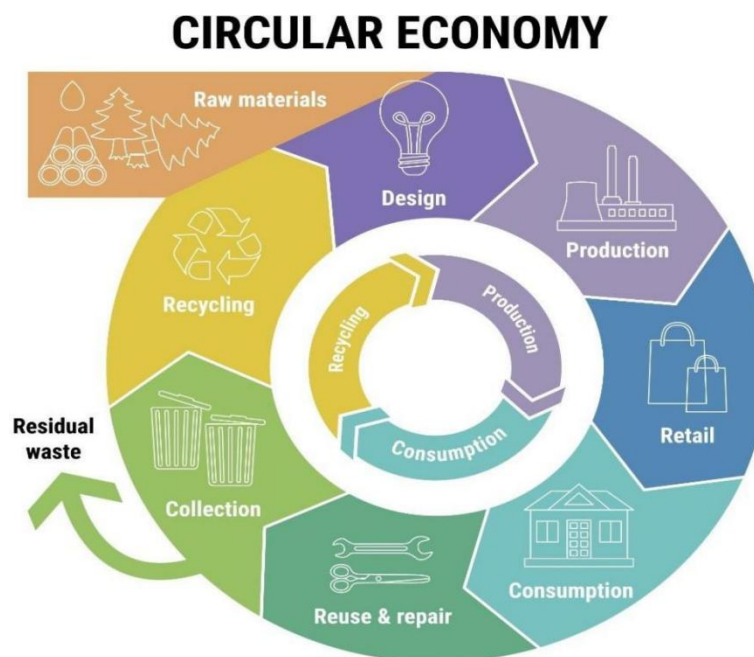
Theoretical framework and literature review

The analytical foundation of this study is grounded in contemporary circular economy theories that conceptualise the transition from linear to circular models as a systemic transformation of business philosophies, rather than a purely technical adjustment. Circular economy is commonly defined as a restorative and regenerative industrial system that replaces the concept of “end-of-life” with superior design of materials, products and business models (Ghisellini et al., 2016; Bojkovska et al., 2023). In the context of agri-food systems, this transformation is particularly relevant due to the high intensity of organic waste, packaging flows and seasonal production cycles.

The implementation of circular strategies in this research is analytically framed through the RESOLVE framework (Regenerate, Share, Optimise, Loop, Virtualise, Exchange), which provides a structured roadmap for identifying points at which resources and by-products can be reintegrated into production cycles (Bojkovska et al., 2023). Early empirical evidence from the Macedonian agri-food sector indicates that the initial phase of circular transition, observed around 2021, was primarily concentrated on the pillars of *Optimise*—through reductions in resource use and waste generation—and *Regenerate*, mainly via the use of renewable energy sources (Bojkovska et al., 2023).

The evolution of circular economy models has seen a significant shift in strategic focus. While early frameworks primarily prioritized waste management, more recent literature emphasizes the limitations of recycling-oriented approaches and calls for a shift towards preventive and redesign-based strategies, as reflected in the expanded 9R hierarchy (Kirchherr et al., 2017).

Figure 1: Circular Economy Value Chain in the Agri-Food Sector



Source: Adapted from Kirchherr et al. (2017)

Within this hierarchy, advanced circularity is achieved through higher-order strategies such as Refuse and Rethink, as well as through the Loop principle, which entails closing material cycles via systematic reuse and recycling. Empirical findings from our 2024 research indicate moderate progress in this direction within the Macedonian agri-food sector, with firms beginning to experiment with closed-loop systems. However, as noted in the reference monograph (Bojkovska et al., 2023), the transition from conceptual awareness to practical implementation is often stalled by a lack of specialized knowledge and high entry costs. Consequently, the capital-intensive nature of such investments remains a significant constraint, creating an 'investment ceiling' that limits the broader diffusion of higher-order circular strategies across the industry.

Digital transformation is increasingly recognised as a critical enabler of circular economy implementation. Technologies such as the Internet of Things (IoT), blockchain and data-driven platforms allow real-time monitoring of resource flows and enhance transparency across the value chain (Bote Alonso et al., 2022). In the agri-food sector, digitalisation extends beyond operational efficiency, functioning as a key mechanism for traceability, accountability and consumer communication.

The introduction of digital tools such as QR codes and Digital Product Passports represents a qualitative shift from traditional marketing towards evidence-based consumer information. This theoretical perspective is strongly supported by empirical findings from 2024, which confirm the mediating role of digitalisation capacity in facilitating both circular

strategy adoption and improved consumer protection. By enabling transparent disclosure of sustainability attributes, digitalisation strengthens trust and market integrity, positioning consumer information as an integral component of circular policy frameworks.

One of the core circular business models identified in the literature is *resource recovery*, which is directly dependent on eco-design principles, particularly in packaging. Eco-design facilitates material separation, recyclability and reuse, thereby enabling the closure of material loops (Bojkovska et al., 2023). In the Macedonian agri-food sector, the adoption of eco-design practices increased from below 5% in 2021 to approximately 12% in 2024, indicating an early but tangible phase of acceptance.

Despite this progress, the relatively slow growth rate suggests that companies continue to face high marginal costs associated with packaging redesign and compliance with environmental standards. This finding reinforces the identification of financial constraints as the primary structural barrier to advanced circular transformation, particularly in small and medium-sized enterprises.

A key theoretical distinction in the circular economy literature concerns the difference between formal environmental compliance and substantive circular innovation. In North Macedonia, alignment with national legislation—such as the Waste Management Law and the Law on Packaging and Packaging Waste—and the adoption of international environmental management systems, including ISO 14001 and EMAS, provide an essential institutional framework for environmental control (ISO, 2015). While ISO 14001 is the most widely adopted standard in the Macedonian agri-food sector, the EU Eco-Management and Audit Scheme (EMAS) represents a higher tier of environmental commitment. EMAS requires not only a functional management system but also mandatory public reporting and verified legal compliance (European Commission, 2009). Our findings suggest that the transition from ISO 14001 toward EMAS-level transparency remains limited, as firms are currently prioritizing basic regulatory adherence ('compliance phase') rather than the rigorous performance tracking and public disclosure required by EMAS.

However, existing studies highlight that formal certification does not automatically translate into strategic commitment to circular innovation. Empirical evidence suggests that a significant proportion of managerial staff in the Macedonian agri-food sector report insufficient knowledge of green entrepreneurship and advanced circular strategies (Bojkovska et al., 2023). This helps explain the observed disconnect between ISO certification and actual readiness for circular investments, positioning the sector predominantly within a “compliance phase”, where certification serves market legitimacy rather than transformative change.

Overall, the period between 2021 and 2024 reflects an evolutionary shift in the Macedonian agri-food sector—from a phase of conceptual awareness towards one characterised by practical implementation constrained by structural and financial barriers. While theoretical understanding, regulatory alignment and digital readiness have improved, the persistence of an “investment ceiling” continues to limit the scaling of advanced 9R strategies. This synthesis underscores the need for policy instruments that move beyond general regulatory frameworks toward targeted economic incentives capable of unlocking circular innovation and accelerating the sector’s transition.

Research methodology

The primary objective of this study is to assess the readiness and capacity of agri-food companies in North Macedonia to transition toward a circular economy. Specifically, the research aims to identify how regulatory knowledge and economic constraints influence the

adoption of circular strategies and consumer protection. Based on the theoretical framework, the following hypotheses are formulated:

- H1: A significant gap exists between formal regulatory awareness and the practical implementation of circular business models in the Macedonian agri-food sector.
- H2: Economic barriers, primarily high investment costs and lack of institutional subsidies, significantly hinder the adoption of 9R circular strategies.
- H3: Digitalisation capacity acts as a fundamental enabler that positively influences the quality of consumer information and protection.

Measuring key constructs: All key constructs were operationalized using multi-item measures developed specifically for the context of the agri-food sector in North Macedonia and informed by previous research on the circular economy. Responses were collected using five-point Likert-type scales (1 = strongly disagree / very low, 5 = strongly agree / very high).

Regulatory knowledge was measured through respondents' self-reported familiarity with national and EU-related policy documents, including the Law on Waste Management, the Law on Packaging and Packaging Waste, the National Waste Management Plan (2020-2030) and the Green Agenda for the Western Balkans.

Economic barriers were operationalized as a composite index capturing perceived financial constraints, including high investment costs, lack of subsidies, administrative burden, lack of qualified personnel and low consumer demand for circular products.

Digitalization capacity was measured through items assessing the use of digital tools for traceability, data management, consumer communication (e.g. QR codes) and process monitoring.

Adoption of circular (9R) strategies was measured through the reported implementation of practices related to resource optimization, waste reduction, eco-design, reuse, recycling and loop-based systems.

Consumer protection and information was operationalized through indicators related to transparency, traceability and the provision of verifiable environmental information to consumers.

Table 1. Measurement of key constructs

Construct	Key indicators / survey items	Scale type
Regulatory Knowledge	Familiarity with the Law on Waste Management, Law on Packaging and Packaging Waste, National Waste Management Plan, Green Agenda for the Western Balkans	5-point Likert
Economic Barriers	Investment costs, availability of subsidies, administrative burden, lack of skilled personnel, low consumer demand	5-point Likert (composite index)
Digitalisation Capacity	Use of traceability tools, data management systems, QR codes, digital process monitoring	5-point Likert
9R Strategy Adoption	Resource optimisation, eco-design practices, reuse, recycling, loop-based systems	5-point Likert

Consumer Protection	Transparency of information, product traceability, provision of verifiable environmental information	5-point Likert
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Source: Author’s own conceptualization based on the research model and survey instrument

The author’s calculated the composite indices as the arithmetic mean of the corresponding items.

Reliability and validity: The internal consistency of the multi-item constructs was assessed using Cronbach's alpha coefficients. All composite indices showed acceptable reliability, with alpha values exceeding the generally accepted threshold of 0.70. Content validity was ensured by aligning with established frameworks for the circular economy (RESOLVE model and 9R hierarchy) and informed by broad circular economy research and context-specific insights drawn from sector reports and policy analyses relevant to the Macedonian agri-food sector.

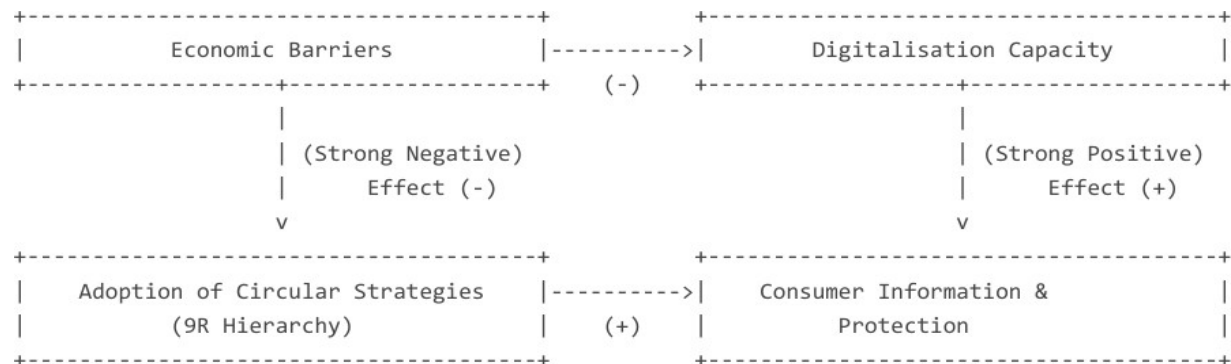
Participant recruitment followed a purposive sampling strategy, targeting decision-makers (owners and senior managers) in the agri-food sector to ensure the quality and relevance of the data. The sampling frame was derived from national business registers and regional chambers of commerce databases. A total of 135 agri-food companies were initially invited to participate via e-mail and telephone calls. Of these, 55 provided complete and valid responses, resulting in a response rate of 40.7%. This response rate is consistent with comparable corporate surveys conducted in transition economies, where access to senior management is often limited. To address potential selection bias, the sample was balanced to reflect the national economic landscape, including micro, small, medium and large enterprises from different sub-sectors. Given the exploratory nature of this research, a sample of 55 companies provides a representative cross-section for identifying key trends and barriers in the transition to a circular economy. The final sample consists of 55 agri-food companies operating in North Macedonia. The sample includes a wide array of sub-sectors, including fruit and vegetable processing (30%), dairy and meat production (30%), bakery and confectionery (20%), the beverage industry (15%), and some other industries including health food and plant-based meal production companies (5%). The sample structure was carefully selected to reflect the national economic landscape: 20% Micro-enterprises (1-10 employees), 40% Small enterprises (11-50 employees), 30% Medium enterprises (51-250 employees), 10% Large enterprises (over 250 employees).

To ensure statistical rigour and reliability, the data were processed using SPSS Statistics package. The following analytical techniques were employed:

1. Descriptive Statistics: To profile the sample and establish baseline levels of awareness and practice.
2. Chi-Square (χ^2) Analysis: To determine the significance of the relationship between company size and levels of regulatory compliance.
3. Pearson Correlation and Multiple Regression: To test the strength and direction of the associations that economic barriers and digitalisation have on circular outcomes.

The research logic is synthesized in the Conceptual Path-Diagram (Figure 2). This model illustrates the structural relationships between the key constructs of the study.

Figure 2. Conceptual path-diagram illustrating the hypothesized relationships between variables (regulatory knowledge, economic barriers, digitalisation capacity and the adoption of circular strategies) in the agri-food sector of North Macedonia



(Note: Positive (+) and negative (-) signs indicate the expected direction of associations.)

Source: Author's own conceptualization based on the research model

The logic of the research paths is interpreted as follows:

- The Regulatory Gap (Regulatory Knowledge → 9R Strategies): The model illustrates that mere awareness of legislation does not directly translate into high-level circular practices, confirming a 'compliance gap' where regulation remains a background factor rather than a driver.
- The Economic Deterrent (Economic Barriers → 9R Strategies): There is a significant negative path (-), identifying financial constraints as the primary 'bottleneck' for 9R hierarchy implementation.
- Digitalisation as a Mediator: The path-based analytical framework suggests that while economic barriers may hinder technological capacity, successful integration of digital tools acts as a powerful engine (+) for enhancing Consumer Information and Protection.
- The Circularity-Consumer Link: Adopting higher-order strategies (Rethink, Redesign) directly improves transparency and consumer rights, bridging the gap between business practice and market needs.

The integration of these constructs within the proposed path-diagram provides the analytical framework for the empirical testing and discussion of the results presented in the following section.

Research Ethics and Data Management

Participation in the survey was strictly voluntary and based on informed consent. All respondents were informed of the study's objectives and were guaranteed complete anonymity and confidentiality; no personal or sensitive corporate data was collected. The data were used solely for academic purposes and stored in aggregate form to prevent identification of individual firms. In line with transparency standards, the data sets are available from the authors upon reasonable request.

Results and discussion

Sample Profile and Regulatory Awareness

This section presents and discusses the empirical findings of the research, fully aligned with the predefined hypotheses and the conceptual model (Figure 2). The analysis follows a

stepwise logic, starting with the descriptive profile of the sample, followed by hypothesis testing and a comparative discussion with previous findings. The analysis tests the structural relationships between regulatory awareness, economic capacity, and the transition to a circular model.

The final sample of 55 agri-food companies reflects the realistic structure of the Macedonian sector, dominated by micro and small enterprises (60%). This structural composition is fundamental for interpreting the results, as smaller firms are typically more vulnerable to financial constraints and administrative complexity in the circular transition. The analysis first examines whether company size is associated with differences in regulatory awareness. As shown in Table 2, the Chi-square results ($\chi^2=14.82$, $p=0.022$) confirm a statistically significant relationship. Large enterprises exhibit substantially higher levels of familiarity with circular legislation, while micro and small firms remain predominantly partially informed.

Table 2. Awareness of circular legislation by company size

Company size	Low awareness	Moderate awareness	High awareness	Total
Micro & small enterprises	45%	33%	22%	100%
Medium & large enterprises	10%	25%	65%	100%

Pearson Chi-Square = 14.82, df = 6, p = 0.022

Source: Author's calculations based on survey data

To further explore the nature of this regulatory gap, the analysis disaggregates awareness across specific legal and strategic documents. This distinction is important, as operational compliance often differs from strategic alignment.

Table 3. Level of awareness of key regulatory and strategic documents

Document	Fully aware	Partially aware	Not aware
Law on Waste Management	62%	31%	7%
Law on Packaging and Packaging Waste	58%	22%	20%
National Waste Management Plan 2020–2026	18%	35%	47%
Green Agenda for the Western Balkans	12%	28%	60%

Source: Author's calculations based on survey data

The results reveal a clear divergence between awareness of legally binding instruments and strategic policy frameworks. While most companies are familiar with core operational laws, nearly half of the respondents are unaware of the National Waste Management Plan (2020–2030), and a majority lack familiarity with the Green Agenda for the Western Balkans. This confirms that the regulatory framework is formally in place but insufficiently communicated in strategic terms, reinforcing the conclusion that H1 reflects a policy implementation gap rather than a legislative absence.

Analysis of Barriers to Circular Transformation

After establishing the regulatory context, the analysis shifts to internal and external barriers that constrain circular implementation. Identifying these barriers is crucial for understanding why awareness does not translate into action (Table 4).

Table 4. Ranking of barriers to circular transformation

Barrier	Mean	Standard Deviation SD	Rank
Lack of financial support/subsidies	4.65	0.52	1
High investment costs for technology	4.42	0.61	2
Complex administrative procedures	3.85	0.84	3
Low consumer awareness	3.72	0.79	4
Lack of skilled personnel/knowledge	3.10	0.95	5

Source: Author's calculations based on survey data

The ranking clearly indicates that economic barriers dominate managerial perceptions. Financial constraints not only outweigh organisational and knowledge-related issues but also directly affect the feasibility of technological investments.

Statistical Analysis and Hypothesis Testing

To further examine the structural relationships proposed in the research, the conceptual relationships illustrated in Figure 2 were empirically tested using the regression model presented in Table 5. This combined correlation and regression analysis allows for a precise evaluation of how regulatory, economic, and digital factors are related to the adoption of circular strategies.

The Pearson correlation reveals two key dynamics (Table 5). First, a strong negative correlation is observed between economic barriers and digitalization capacity, indicating that financial constraints represent a major obstacle to digital upgrading and are associated with lower adoption of a circular strategy in the agri-food sector. Second, the strong positive correlation between digitalization capacity and consumer protection ($r = 0.64$, $p < 0.001$)

provides empirical support for Hypothesis H3, confirming that digital tools play a key role in improving transparency, traceability and consumer information within circular agri-food systems.

Table 5. Correlation matrix and multiple regression results for Circular Strategy Adoption

Variables	(1)	(2)	(3)	(4)	Standardised β	Standard Error (SE)	Sig. (p)
(1) Regulatory knowledge	1				0.214	0.082	0.036
(2) Economic barriers	-0.42*	1			-0.412	0.091	< 0.001

(3) Digitalisation capacity	0.35*	-0.58*	1		0.385	0.104	0.001
(4) Consumer protection	0.28*	-0.31*	0.64*	1	—	—	—
Model Fit:	$R^2 = 0.52$	Adj. $R^2 = 0.49$	F = 18.42	$p < 0.001$			

Note: Correlation is significant at the 0.05 level. VIF values for all predictors are below 2.0, indicating no multicollinearity concerns. Sig. (p) denotes the p-value of the regression coefficients.

Source: Author's calculations based on survey data

Before interpreting the regression results, standard diagnostic checks were performed. No significant violations of the assumptions of normality, homoscedasticity, or multicollinearity (VIF values below the conventional threshold) were detected. Given the observational nature of the data, the analysis focuses on statistically significant associations rather than causal links.

The regression analysis further assesses the relative explanatory power of the independent variables in predicting circular strategy adoption. Economic barriers emerged as the strongest negative predictor ($\beta = -0.412$, $p < 0.001$), providing strong empirical support for Hypothesis H2.

Digitalisation capacity remains a significant positive driver ($\beta = 0.385$, $p = 0.001$), while regulatory knowledge also demonstrates a statistically significant positive association with circular strategy adoption ($\beta = 0.214$, $p = 0.036$), supporting Hypothesis H1. Overall, the model accounts for 52% of the variance in circular strategy adoption ($R^2 = 0.52$). These results highlight the critical role of digitalisation in facilitating the transition toward a circular agri-food sector, while simultaneously identifying economic constraints as the primary inhibiting factor.

The Role of Environmental Certification and Comparative Analysis (2021–2024)

An exploratory comparison between ISO 14001-certified and non-certified firms reveals no substantial difference in circular readiness, suggesting that certification primarily serves as a compliance-oriented instrument for market legitimacy rather than as a driver of strategic innovation. The transition to the more rigorous EU Eco-Management and Audit Scheme (EMAS) remains almost non-existent due to high marginal costs and the absence of financial incentives for SMEs. As further detailed in the Conclusions, this stagnation confirms an “investment ceiling” that prevents a deeper circular transformation.

To capture the dynamic evolution of circular economy practices, a comparative analysis of key indicators between 2021 and 2024 was undertaken. For the purposes of this analysis, data from the Monograph "Circular Economy - A Global Concept for Sustainability" (Bojkovska K. et al., 2023) were used as a reference base, which refers to research conducted in 2021. This allows for precise monitoring of the progress of the Macedonian agri-food sector over a period of three years. As summarised in Table 6, the findings indicate a gradual transition from conceptual engagement toward early-stage implementation of circular strategies. While digitalisation and consumer information mechanisms have expanded notably, progress in eco-design and advanced circular practices remains slow. The comparison further reveals a structural shift in perceived

barriers—from limited awareness in 2021 to financial constraints in 2024—underscoring the need for targeted economic support mechanisms to accelerate circular transformation.

Table 6. Comparative analysis of circular economy indicators (2021 vs. 2024).

Indicator	2021 (according to Bojkovska K. et al., 2023)	2024	Trend
RESOLVE model application	Optimise, Regenerate	Inclusion of Loop	Moderate progress
Eco-design of packaging	<5%	~12%	Slow growth
Digitalisation	Almost absent	18%	Significant increase
Consumer information	Traditional marketing	QR codes, digital channels	Transparency shift
Main barrier	Lack of awareness	Financial constraints	Structural shift

Source: Author's calculations based on survey data and Bojkovska K. et al., 2023

The findings in Table 6 indicate a gradual shift from conceptual engagement to early-stage implementation of circular strategies. While digitalization and consumer information mechanisms have expanded significantly (increasing from almost non-existent to 18%), progress in ecodesign and advanced circular practices remains slow. The comparison further reveals a structural shift in perceived barriers – from limited awareness in 2021 to financial constraints in 2024 – highlighting the need for targeted economic support mechanisms to accelerate the circular transformation.

The comparison reveals a clear transition from conceptual uncertainty in 2021 toward implementation constrained primarily by financial limitations in 2024. While awareness and digital capabilities have improved, the absence of targeted financial instruments continues to hinder the scaling of circular practices across the sector.

Conclusions

The findings of this study demonstrate that the circular transition in the Republic of North Macedonia has entered a compliance-driven but investment-constrained phase.

The findings should be interpreted as indicative of statistically significant associations, not definitive causality, given the observational nature of the study design. Instead, the sector appears to have reached an “investment ceiling”, where regulatory compliance is achieved, but deeper circular transformation remains financially unattainable for most firms.

The validation of the research hypotheses confirms three structural dynamics shaping the circular transition. First, although awareness of legally binding waste management regulations is relatively high, a substantial gap persists in the understanding of strategic policy frameworks, particularly the Green Agenda for the Western Balkans. This finding indicates that the existing regulatory architecture is not deficient in formal terms but remains weakly embedded at the strategic and operational levels, especially among micro and small enterprises.

Second, economic constraints emerge as the dominant barrier to circular strategy adoption. High investment costs and limited access to financial support exert a strong negative

predictor for the implementation of 9R strategies ($\beta = -0.412$), outweighing organisational or knowledge-related limitations. The results clearly show that the main obstacle to circular transformation is not resistance or lack of awareness, but insufficient economic capacity to absorb the costs of technological and process-related innovation.

Third, digitalisation plays a critical enabling role in the circular transition. Strong empirical links between digital capacity and consumer protection ($r = 0.64$) demonstrate that digital tools significantly associated with higher transparency, traceability, and trust within agri-food value chains. While digitalisation alone cannot eliminate financial constraints, it provides a practical mechanism through which firms can improve circular performance and partially mitigate structural limitations.

The comparative analysis between 2021 and 2024 reveals a clear structural shift in the nature of barriers to circular economy adoption. Whereas limited awareness dominated earlier stages of transition, financial constraints now represent the primary bottleneck. This transition underscores the maturation of the sector from conceptual engagement toward early-stage implementation, while simultaneously exposing the absence of adequate economic instruments to support scaling.

From a policy perspective, the findings suggest that future interventions must move beyond general regulatory alignment toward targeted, outcome-oriented economic support mechanisms. Priority should be given to: direct innovation grants aimed at reducing the investment burden of 9R technologies for SMEs, incentives for digital traceability systems that strengthen consumer information and market transparency, and performance-based reward schemes that prioritise measurable waste reduction and circular outcomes over formal compliance instruments such as ISO 14001 certification.

The research highlights a significant institutional paradox: firms achieve formal environmental control through ISO 14001, yet they remain at an 'investment ceiling' that prevents them from adopting superior European standards like EMAS. To bridge this gap, policy interventions in North Macedonia should shift from promoting general certification toward performance-based reward schemes that specifically offset the costs of EMAS-level transparency and high-order 9R strategies.

In conclusion, without effectively bridging the gap between widespread awareness and limited investment capacity, the circular potential of the Macedonian agri-food sector will remain largely unrealised. A successful transition will depend not on additional regulation, but on the strategic alignment of financial, digital, and policy instruments capable of transforming compliance into genuine circular transformation.

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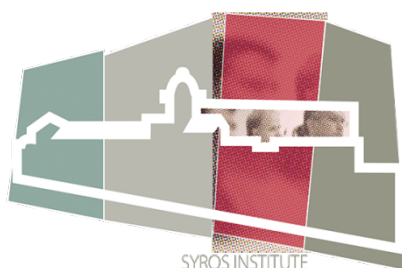
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