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# Approaches and perspectives on the transition to the circular economy in the European Union

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**Introduction:** The transition to a circular economy is a key pillar of European sustainable development. However, in the current context, shaped by multiple crises and geopolitical conflicts, the efficiency and resilience of this transition are of particular concern. European policymakers and national authorities must adapt their approaches to mitigate risks posed by external factors while ensuring progress towards European sustainability goals. This study analyzes the transition to the European circular economy from 2010 to 2022, assessing key economic and environmental variables.

**Methods:** The study employs an econometric approach using panel data from the 27 EU Member States. A multiple linear regression model with fixed effects panel data is applied alongside spectral analysis and descriptive statistics to examine the relationships between private investment, gross value added, municipal waste recycling rates, recyclable material flows, and greenhouse gas emissions. These methods allow for an in-depth evaluation of the factors influencing the efficiency of the circular economy transition.

**Results:** Findings indicate that private investment and the integration of recyclable materials significantly enhance the efficiency of the circular economy. However, progress varies across Member States due to regional disparities, inadequate recycling infrastructure, and inefficient municipal waste management. High-emission countries face greater challenges in achieving environmental targets, demonstrating the need for tailored and resilient policy measures.

**Discussion:** The results highlight the necessity of public policies that promote the attractiveness of circular economy sectors, reduce regional disparities, and improve waste management infrastructure. Additionally, the study emphasizes the importance of a coordinated and region-specific approach to accelerate the transition towards a sustainable circular economy. By integrating seasonal and regional analyses, the research contributes to the literature by offering a nuanced understanding of the factors affecting circular economy progress. These insights are valuable for supranational policymakers in developing effective strategies to enhance circular economy resilience at the European level.

KEYWORDS

**circular economy, econometric efficiency model, public policies, regional disparities, sustainability**

## 1 Introduction

The economic evolution and climate change accelerated with the entry into the new millennium have been major elements of change in the traditional approaches to economic activity and in this context the circular economy has developed and crystallized in the European Union under the impact of the regulations of the European forums on the protection of natural resources and sustainable development. With a view to achieving the objectives of sustainability and reducing the impact of economic activity on the environment, a series of strategic instruments have been developed and adopted at EU level, which have favored the development of the circular economy. The new Circular Economy Action Plan adopted by the European Commission in 2020 (European Union, 2020) developed against the backdrop of the European Green Pact (European Commission, 2023d) which has been an important measure in the fight against climate change sought by the European forums. The new Circular Economy Action Plan provides for the promotion of sustainable products to European standards, incentives for consumers to choose products with low environmental impact, the promotion of resource-efficient sectors (such as information technology) and the radical streamlining of polluting sectors (plastics production and processing, textiles, construction, automotive, food). Thus, the European Union has proposed 35 action measures to achieve a sustainable impact on the environment by reducing pollution and waste, measures designed to make the circular economy a beneficial tool for European communities and to position Europe as a global leader in this field.

Some of the most recent initiatives are aimed at restricting microplastics, regulating pellet wastage, creating eco-labeling standards and increasing the life of goods through recycling and repair. In the longer term, European actions include revisions of the packaging, textiles and shrinkage directives to stimulate circular models in the economy.

In order to monitor progress in implementing the circular economy, the European Commission adopted a revised monitoring framework in 2023 (Eurostat, 2023a) which contains additional indicators for monitoring the environmental impact of economic activity such as the carbon footprint of materials and resource productivity, used as expressions of material efficiency. Through this framework, the European fora have set out to monitor European resource consumption in relation to planetary limits and in relation to the climate neutrality and circular transition objectives adopted at EU level under the European Green Pact.

The transition to a circular economy is an essential component of sustainable development at European level, with the aim of reducing excessive consumption of resources and limiting the environmental impact of economic activities. In the context of the current multiple crises and geopolitical conflicts, the efficiency and resilience of this process is of paramount importance for European and national policymakers.

Although the circular economy has become a central topic in the economic and environmental literature, many aspects of the transition towards this model remain insufficiently explored. Existing analyses focus either on conceptual and normative approaches or on sectoral case studies, without providing an integrated view on the determinants of circular economy efficiency at the European level (Baldassarre, 2025; De Pascale et al., 2023; Kaya et al., 2023). In particular, there are three main areas where the current literature (Agovino et al., 2024; Bianchi et al., 2023; Dey et al., 2022; Gura et al., 2023) has important gaps: The econometric dimension of circular economy efficiency; Regional disparities and seasonality; The role of public policies in optimizing the transition. As regards the econometric dimension of circular economy efficiency, most qualitative studies highlight the benefits of the transition to the circular economy, but few studies apply robust econometric models to empirically assess the impact of economic and environmental factors on this process. A systematic investigation of the relationships between private investment, materials recycling, circular trade flows and economic and environmental sustainability is needed.

The current literature (Marks et al., 2023; Sánchez-García et al., 2024) addresses the development of the circular economy unevenly across EU Member States, but without integrating a detailed analysis of the factors driving these differences. The lack of recycling infrastructure, differences in national policies and the fragmented nature of markets for recyclable materials are aspects that affect the homogeneous implementation of the circular economy, and the impact of seasonality on recycling and trade flows of recycled materials is almost non-existent in the literature. Although many studies emphasize the importance of strategies to support the circular economy, the analysis of the concrete impact of various public policy measures on economic and environmental efficiency is still limited. There is no clear comparative framework to assess to what extent policies to stimulate investment, harmonization of recycling regulations or subsidies for circular technologies actually contribute to accelerating this process.

In this context, the present study focuses on analyzing the transition towards the circular economy in the European Union, with an emphasis on identifying the determinants of the efficiency of this process and on formulating effective public policies to accelerate progress.

The central issue addressed by the research is related to assessing how private investment, material recycling and circular trade flows influence the efficiency of the transition to the circular economy in the EU Member States. In this respect, the study raises the following key questions:

- What are the main economic and environmental variables contributing to the efficiency of the circular economy?
- How do private investment and the integration of recyclables influence economic and environmental performance?
- What role do regional disparities and seasonality play in the transition to the circular economy?
- What public policies are needed to support a faster and more uniform transition at European level?

To answer these questions, the study uses an econometric model based on panel data for the 27 EU Member States, analyzing the relationships between variables such as private investment, gross value added, recycling rates, recyclables flows and greenhouse gas emissions. This methodology allows the identification of significant correlations and provides a solid basis for the formulation of informed public policies.

The specific research objectives are:

1. Identifying how regional differences and seasonality influence the efficiency of the transition to the circular economy.
2. Determining key variables that contribute to reducing pollution and increasing the efficiency of the circular economy.
3. Analyze the attractiveness of the circular economy sector in the labor market.
4. Developing recommendations to address regional disparities and support a sustainable transition to the circular economy at European level.

The results obtained contribute to the literature by providing an integrated perspective on the economic and structural factors that determine the efficiency of the transition to the circular economy, emphasizing the importance of coherent public policies and a differentiated approach according to the regional specificities of the Member States. The results are useful for policymakers at supranational level in developing effective strategies to accelerate progress towards a resilient circular economy.

The study continues with the presentation of the literature, the methodology used in the research and the results and discussions on the transition to the circular economy in the European area. At the end of the study are presenting the main conclusions of the research.

## 2 Literature review

The literature on the circular economy has grown significantly recently, reflecting the importance of the transition from linear economic models to regenerative approaches. Existing studies analyze the circular economy concept from various perspectives, focusing on conceptual issues, performance indicators, regional disparities and barriers to implementation. Within the European Union, recent research focuses on assessing the efficiency of the transition to the circular economy, with a focus on the role of investment, public policy and technological innovation. This chapter synthesizes the relevant contributions from the literature, providing a conceptual framework for the analysis of the circular economy and identifying existing gaps to inform further research. In this section we analyze the conceptual framework of the circular economy, key indicators for monitoring efficiency, regional disparities in implementation, the role of public policy, challenges and barriers encountered, and emerging trends and research gaps.

### 2.1 Conceptual framework of the circular economy

The circular economy represents a fundamental shift from the traditional linear paradigm of "take, make, throw away," offering an approach that prioritizes waste reduction, reuse and recycling of resources. This transition aims not only to extend the life cycle of products and materials, but also to minimize the economic impact on the environment and reduce pressure on finite natural resources. In contrast to the traditional economic model, the circular economy is based on three key principles: eliminating waste and pollution, keeping products and materials in use for as long as possible and regenerating natural systems (Velenturf and Purnell, 2021).

The conceptualization of the circular economy is closely related to the theory of ecological economics, which promotes the idea of "decoupling" economic growth from excessive consumption of resources. The authors Kirchherr et al. (2023) explores the possibility of decoupling economic growth from environmental impacts, emphasizing that absolute decoupling is rare and difficult to achieve. The authors emphasize the importance of integrated policies and structural transformations, such as technological innovation and resource efficiency, to achieve long-term sustainability. According to the authors Suchek et al. (2021), the circular economy offers a sustainable solution to economic and environmental problems, supporting both resource efficiency and industrial innovation. Recent studies have extended this view of the circular economy, emphasizing the need for cross-sectoral collaboration involving actors from industry, government, academia and civil society to integrate circular models into all aspects of the economy. For example, the authors Awan et al. (2022), Bressanelli et al. (2022); Sonar et al. (2024) emphasizes that the transition to a circular economy cannot be achieved without strategic coordination across sectors, as the interdependencies between global value chains and the local economy play a key role in the successful implementation of circular principles. Along the same lines, other authors Kandpal et al. (2024), Rodríguez-Espíndola et al. (2022), Sánchez-García et al. (2024); Wang et al. (2023) argues that the circular economy depends on a holistic approach in which traditional sectors adopt renewable and sustainable processes, while technological innovations help maximize resource efficiency. However, in other studies (Danvers et al., 2023; Geerken et al., 2022; Lepore et al., 2023) emphasizes the importance of collaboration at the public policy level, suggesting that a well-structured cross-sectoral dialogue can reduce the institutional and technological barriers that limit the uptake of the circular economy.

The European Union has adopted the circular economy as a central pillar of its sustainable development strategies, highlighting this in the European Green Pact and the 2020 Circular Economy Action Plan. These initiatives aim to promote the sustainable use of resources, reduce carbon emissions and position Europe as a global leader in implementing the circular economy. Specific actions include revising packaging directives, promoting eco-design and creating a single market for recyclable materials (European Commission, 2024c). The development of the circular economy in the European Union has been approached from a variety of perspectives, including the analysis of economic instruments, the impact of eco-innovation and recycling, and the role of innovation in stimulating the transition towards sustainable models. Platon et al. (Platon et al., 2024) emphasizes the use of economic instruments as the main means to support the circular economy, with a particular focus on the EU and Romanian context. The study emphasizes the importance of integrated policies that facilitate the transition, especially in emerging economies.

Current research explores the practical applicability of the circular economy in various economic sectors and its impact on regional development. For example, the authors Sakao et al. (2024), Salvador et al. (2020), Smol et al. (2024), identifies circular business models that include product innovation, advanced recycling and extensive use of secondary materials. These models have been tested in sectors such as textiles, construction and automotive, demonstrating significant potential for reducing emissions and optimizing resources.

In addition, recent studies highlight the role of digital technologies in supporting the circular economy. Blockchain, for example, is being used to ensure the traceability of materials and artificial intelligence (AI) is optimizing recycling and reuse processes (Bashynska and Prokopenko, 2024; Bułkowska et al., 2024; Jiang et al., 2023; Verma et al., 2022). These technologies facilitate the implementation of the circular economy by automating processes and reducing logistics costs.

At the same time, the analysis of the effectiveness of the circular economy through performance indicators such as the rate of circular use of materials and private investment in circular sectors is a central topic in the literature (Calzolari et al., 2022; De Pascale et al., 2021; Halkos and Aslanidis, 2023; Rincón-Moreno et al., 2021; Silvestri et al., 2024).

At EU level, research has found significant positive correlations between the adoption of circular economy principles and sustainable economic growth in developed countries such as Germany and the Netherlands, which have advanced recycling infrastructures, coherent public policies and a high awareness of the benefits of the circular economy. These countries have demonstrated the ability to leverage investments in circular sectors, to effectively integrate recyclables into production chains and to promote innovation through favorable regulations and fiscal incentives (Alivojvodic and Kokalj, 2024; ENEL, 2020; Grybaitė and Burinskienė, 2024; Radivojević et al., 2024).

On the other hand, emerging economies such as Romania and Bulgaria face significant obstacles, including underdeveloped infrastructures for waste management, limited access to advanced recycling technologies and low levels of investment in the circular economy. Recent studies show that these countries are often hampered by institutional and behavioral barriers, such as the lack of uniform legislation and adequate financial support mechanisms (European Commission, 2023b; Laureti et al., 2024; Pantcheva, 2023). Moreover, regional disparities are also reflected in differences in the recycling rate of municipal waste, which in Romania and Bulgaria is considerably below the European average, thus affecting the transition of these economies towards a circular model (Eurostat, 2024d).

These observations underline the need for tailored interventions, such as European funding programmes for the development of circular infrastructure, harmonization of national regulations and the creation of functioning markets for recyclables, to reduce disparities and facilitate a smooth transition to the circular economy. Thus, the differences between developed and emerging economies in the European Union demonstrate the importance of a flexible and tailored policy framework supported by cross-sectoral collaboration and supranational initiatives.

The circular economy is at the center of a growing discussion on sustainability, but its implementation remains uneven, influenced by regional and structural factors. Challenges identified include the lack of adequate recycling infrastructure in some regions, organizational resistance to change and the increasing complexity of global supply chains. Further research is also needed on the interaction between public policies and the uptake of the circular economy, particularly in key economic sectors such as construction and information technology. The circular economy provides a sound conceptual and practical framework to support the transition towards sustainable economic models. While many obstacles remain, recent initiatives and research show significant potential for economic transformation. To fully realize this potential, it is necessary to strengthen collaboration between governments, industry and academia, thus ensuring an effective and tailored integration of circular economy principles.

## 2.2 Key indicators for assessing the effectiveness of the circular economy

Assessing progress towards a circular economy requires the use of specific indicators that reflect both the economic and environmental dimensions of this transformative process. These indicators are essential for monitoring the implementation of circular economy principles, identifying weaknesses and highlighting opportunities for improvement, providing a solid basis for the development of public strategies and policies.

Among the most relevant indicators are the recycling rate of municipal waste (RRMW), the circular material use rate (CMUR) and private investment in circular economy sectors (PIGVA). The recycling rate of municipal waste reflects the efficiency of waste management and the uptake of recycling practices at local level. According to a European Environment Agency (European Environment Agency, 2023b), Countries such as Germany, with a recycling rate of 68%, demonstrate that investment in infrastructure and public education can lead to remarkable performance. The circular material use rate measures the proportion of secondary materials used as a proportion of total material consumption and is an indicator of the circularity of the economy. Countries like the Netherlands, with a circular use rate of 27.5% (Eurostat, 2023b), is at the top of the rankings thanks to advanced resource recycling and reuse strategies. In this vein, Platon et al. (2022) emphasize that recycling and innovation are key factors contributing to increasing the rate of circular material use and improving the efficiency of the circular economy in the European Union. Their study provides an empirical basis for understanding how these elements can be integrated into sustainable economic policies and strategies. Private investment and gross value added in circular economy sectors reflect their economic contribution, underlining the importance of attracting private funds to expand and strengthen the circular economy (Ghisellini et al., 2016; Goh et al., 2024; Marino and Pariso, 2020; Morelli et al., 2024; Van Opstal et al., 2024).

Recent studies underline the importance of standardizing these indicators, which facilitates comparisons between EU Member States and promotes a unified approach in implementing the circular economy. A number of studies (Coluccia et al., 2024; Dragomir and Dumitru, 2024; Silvestri et al., 2024; Voukkali et al., 2023) highlights the role of these indicators in highlighting regional disparities. While developed countries are making steady progress, emerging economies, such as Romania and Bulgaria, face significant difficulties in adopting the principles of the circular economy due to poor infrastructure, low levels of investment and limited access to advanced technologies (European Commission, 2022; Laureti et al., 2024; OECD, 2022; Tutak and Brodny, 2024).

Another central issue in the literature is the integration of advanced technologies such as artificial intelligence and blockchain to optimize material traceability and improve recycling processes. These innovations contribute significantly to increasing the efficiency of circularity indicators and reducing costs associated with resource management (Chauhan et al., 2022; Du et al., 2024; Hariyani et al., 2024).

However, there are limitations to the use of current indicators. Authors Brusselaers et al. (2022), Calisto Friant et al. (2020), Harris et al. (2021), Van Hoof et al. (2018) arguing that they do not always capture the complexity of interactions between the circular economy and external factors such as climate change or global trade policies. The lack of up-to-date and uniform data across Member States can also compromise accurate monitoring of progress. To increase the relevance and usefulness of these measurement tools, future research should develop indicators that include both economic and social variables to better reflect the dynamics of the circular economy. At the same time, integrating regional and seasonal perspectives could provide a more complete picture of the transition to the circular economy, helping to reduce disparities between Member States and accelerate the EU's progress in this area (European Commission, 2023a; European Committee of the Regions, 2024). In this way, through the effective use of core indicators, the European Union can identify and implement interventions needed to reduce regional disparities, support emerging economies and promote a sustainable economic model. These indicators not only measure performance but also guide decision-making processes, contributing to the success of the transition to a circular economy.

## 2.3 Regional disparities in implementing the circular economy

The implementation of the circular economy in the European Union reveals significant disparities between developed and emerging countries. These differences are driven by factors such as level of economic development, recycling infrastructure, national legislation and public awareness of the benefits of the circular economy. While some countries, such as Germany and the Netherlands, are at the forefront of the circular economy, others, such as Romania and Malta, face major challenges that limit their progress in this area. Countries such as Germany and the Netherlands have invested significantly in recycling infrastructure and public policies that promote material reuse and waste reduction. Given its high recycling rate of municipal waste, Germany is an example of best practice in the circular economy with an integrated collection, sorting and recycling system. In addition, well-coordinated national policies such as the Packaging Guarantee Scheme have contributed to reducing pollution and raising public awareness (OECD, 2024a). In contrast, emerging countries such as Romania and Malta face underdeveloped infrastructure and low recycling rates (Laureti et al., 2024; Pricope et al., 2024). These countries face problems such as a lack of funding for infrastructure upgrades, ineffective implementation of EU legislation and limited public awareness of the benefits of the circular economy. In addition, institutional resistance and behavioral barriers continue to hinder the implementation of sustainable solutions.

Regional disparities in the implementation of the circular economy are closely linked to the level of economic development and the resources available for investment in circular sectors. There are studies (Agrawal et al., 2023; Kumar et al., 2024; Lahane and Kant, 2022; Siderius and Zink, 2023) which highlighted that more advanced economies have the capacity to allocate significant funds to infrastructure and education, leading to superior circularity performance. In contrast, emerging economies, which face budget constraints, have difficulties in developing infrastructure and attracting private investment (Schröder et al., 2021; Schröder and Barrie, 2024).

This regional divide highlights the need for tailored policies to support low-performing countries. Diverse studies (Oyejobi et al., 2024; Sarkhoshkalat et al., 2024; Stier et al., 2024) suggests that the implementation of European funding programs dedicated to upgrading recycling infrastructure and creating markets for recyclable materials could help bridge the gaps. Ghisellini et al. (2016) also recommend the development of public awareness campaigns and the promotion of cooperation between Member States to transfer knowledge and best practices (Forastero, 2023; Moustairas et al., 2022).

Recent research shows that emerging economies in Central and Eastern Europe would benefit from an integrated approach combining European funding with results-oriented national policies (Czyżewski and Kryszak, 2023; Pina and Sicari, 2021), investment in advanced recycling technologies and training for circular economy jobs can boost progress in these regions (Ciot, 2022; Dincă et al., 2022). Furthermore, harmonization of regulations on recycling standards at EU level could reduce trade barriers and encourage more effective integration of circular economy principles.

Regional disparities in the implementation of the circular economy reflect the complexity of the transition to a sustainable economic model at European level. To overcome these challenges, it is essential to develop tailor-made public policies, supported by adequate funding and cooperation between Member States. Investments in infrastructure, education and innovative technologies will play a crucial role in bridging the gaps and promoting a uniform and efficient circular economy across the European Union.

## 2.4 Public policies, challenges and emerging trends in the transition to the circular economy

The effective transition to the circular economy is profoundly influenced by the quality and coherence of public policies, but also by the structural and technological challenges that constrain its implementation. Public policies play a key role in facilitating the transition and recent research by various authors (Ahmadov et al., 2022; Chenavaz and Dimitrov, 2024; Nunes et al., 2023; Ren and Albrecht, 2023) highlights the effectiveness of economic incentives such as tax breaks for investments in circular technologies. These contribute significantly to accelerating the necessary changes, all of which are essential levers for achieving sustainability goals. Eco-innovation and recycling play a key role in accelerating the transition to the circular economy, and this requires well-structured public policies. The study by Platon et al. (2023) emphasizes the importance of investing in innovation and creating advanced recycling infrastructures to reduce the consumption of raw resources and stimulate the adoption of circular economy principles.

However, the transition to the circular economy faces many challenges. Technological limitations in recycling complex materials such as plastics remain a significant barrier. Behavioural barriers, such as organizational resistance to change, and structural barriers, related to the lack of adequate infrastructure, also complicate the implementation process. Diverse studies (Sarja et al., 2021; Thirumal et al., 2024; Trevisan et al., 2023; Wang et al., 2022) stresses the importance of addressing these obstacles to maximize the potential of the circular economy. In addition, recent economic crises and geopolitical disruptions, such as the COVID-19 pandemic, have exacerbated vulnerabilities in global supply chains, undermining progress in this area.

Technological progress brings promising prospects for the circular economy through the integration of digital technologies such as blockchain, which facilitates the traceability of materials, and artificial intelligence, which optimizes resource flows and improves the efficiency of recycling and reuse processes. However, there are studies (Maguire and Robson, 2023; Oladapo et al., 2024; Rao et al., 2024; Rodríguez-Pose and Bartalucci, 2023) which draw attention to the existing gaps in understanding the socio-economic impacts of these technologies, especially in low-income regions, highlighting the need for future research to develop inclusive strategies to support the adoption of the circular economy on a global scale.

Thus, the success of the transition to the circular economy depends on the effective interplay between well-structured public policies, technological innovation and addressing existing challenges. Continuous adaptation of strategies and investments in education and infrastructure remain crucial elements to promote a sustainable and inclusive circular economy.

The literature review highlights the complexity of the transition to the circular economy, emphasizing the crucial role of public policies, cross-sectoral collaboration and technological investments in achieving sustainability goals.

While there are positive examples in developed countries, regional disparities and technological and behavioral barriers remain significant challenges, the success of the transition depends on integrating coordinated and tailored strategies that address the specific needs of each region.

Notwithstanding the challenges, the emergence of digital technologies, such as blockchain and artificial intelligence, opens up significant opportunities for improving circular processes and reducing inequalities. However, further research is needed to fully understand the socio-economic impacts of the circular economy and to develop inclusive and sustainable solutions. The transition to the circular economy is not only a challenge but also a major opportunity for redefining global economic and environmental sustainability.

## 3 Methodology

To position our study within the existing literature, we draw upon several key works that validate the application of panel econometric models in circular economy research. Knäble et al. (2022) and Aydınbaş and Erdinç (2023) demonstrated the utility of panel data for examining the interdependencies between economic, environmental, and social dimensions of the circular economy. Georgescu et al. (2022) employed fixed effects models and Granger causality tests to explore relationships between waste generation, recycling rates, and economic growth. Tantau et al. (2018) used panel regression to assess recycling efficiency, while Hysa et al. (2020) introduced an integrated model combining sustainability, innovation, and economic growth within the circular economy framework. Current study builds on this foundation by addressing gaps in the literature. The study emphasizes regional disparities and seasonal effects, offering a nuanced perspective on the uneven progress of circular economy transitions across EU member states. It incorporates trade in recyclable raw materials (TRRM) and labor market impacts to broaden the scope of analysis, providing a comprehensive understanding of the circular economy's efficiency. The findings are situated within the policy framework of the EU Green Deal, offering actionable insights for regional and supranational governance. By employing fixed effects models, the analysis ensures robustness in identifying causal relationships, accounting for unobserved heterogeneity across regions and time periods.

To answer the research questions, the study uses an econometric model based on panel data for the 27 EU Member States, analyzing the relationships between variables such as private investment, gross value added, recycling rates, recyclables flows and greenhouse gas emissions (see Table 1).

This methodology allows significant correlations to be identified and provides a sound basis for the formulation of informed public policy.

Although the transition to the circular economy is, by its nature, a non-linear process due to its regenerative nature and the complexity of its interdependencies, the use of a linear regression model with fixed effects is justified from several perspectives: linear models allow the identification of direct and interpretable relationships between the explanatory variables and the dependent variable (this is especially useful in public policy analysis, where decision makers need clear and actionable conclusions); fixed effects models eliminate the influences of time constant variables (such as initial infrastructure or political culture) and allow more precise assessment of the relationships between dynamic variables. Panel data-based econometrics is an appropriate method for this study as it allows the simultaneous analysis of temporal and spatial variations, providing a comprehensive picture of the dynamics of the circular economy in the Member States. Tracking the evolution of economic and environmental indicators over time (2010–2022) allows to assess the impact of implemented policies on the transition to the circular economy. Analysis of differences between Member States identifies regional disparities and specific factors influencing the effectiveness of the circular economy in each area. The use of fixed and random effects models ensures that the impact of independent factors is assessed independently of other contextual variables.The outline of the study aims to assess the efficiency of the transition to the circular economy based on determining the causalities between the transition to the circular economy and the reduction of pollution (i.e., increased recycling of municipal waste) on the one hand and the growth of the circular economy sector (through trade in recycled materials) on the other hand. Subsequently, aspects of increased trade in the circular economy and its impact on greenhouse gas emissions in the European Union under Green Deal implementation will be

TABLE 1 Presentation of indicators.

| Justification | Symbol | Indicators | Measure | Source |
|---|---|---|---|---|
| The number of people employed in circular sectors reflects the attractiveness of the circular economy on the labor market, an important social aspect | PSECE | Persons employed in circular economy sectors | Persons employed | Eurostat (2022a) |
| Trade flows of recyclable materials represent the dynamics of trade in recyclable materials between Member States and indicates the functioning of circular markets. This indicator is essential for assessing the impact of circular trade on the efficiency of the economy, reflecting the integration and valorization of recycled resources at transnational level | TRRM | Trade in recyclable raw materials | Tons | Eurostat (2024f) |
| Circular material utilization rate provides a direct picture of the efficiency of the circular economy by indicating the proportion of recycled materials used | CMUR | Circular material use rate | % | Eurostat (2024a) |
| Material flows of recyclable materials represent the level of integration of secondary materials into economic chains, a critical component of circularity | MFCE | Material flows for circular economy - Sankey diagram data | Thousand tonnes | Eurostat (2024c) |
| Recycling rate of municipal waste is a key indicator of the effectiveness of waste management and the adoption of circular practices at local level | RRMW | Recycling rate of municipal waste | Percentage | Eurostat (2024e) |
| Private investments reflect the economic commitment to the circular economy and are essential for the development of infrastructure and sustainable technologies | PIGVA | Private investment and gross added value related to circular economy sectors | Million euro | Eurostat (2022b) |
| Greenhouse Gas Emissions measures the environmental impact of economic activities and is essential for assessing sustainability | GHGE | Greenhouse gases emissions from production activities | Kilograms *per capita* | Eurostat (2024b) |

Source: Elaborated by authors based on Eurostat data.

followed up in conjunction with the quantification of the effectiveness calculated by using resource circularity rates. The efficiency of the transition to the circular economy will also take into account the impact of this branch on the labor market (i.e., by measuring the attractiveness of the branch). The efficiency model is characterized based on the logic scheme presented in Figure 1.

The validation of the following working hypotheses was pursued during the research:

**H1.** Increasing the employment in the circular economy sector significantly enhances the efficiency of the circular economy transition by boosting investments and value-added creation in circular industries.

**H2.** Reducing trade inefficiencies in recyclable raw materials is essential to mitigate negative effects on the circular economy's efficiency.

**H3.** Seasonal variations significantly influence the efficiency of the circular economy by affecting the utilization rates of circular materials, reflecting fluctuations in resource availability and recycling processes.

**H4.** Increasing the attractiveness of the sector and the flows of recyclable materials is essential for an efficient transition to the circular economy.

The panel regression model with fixed effects involves testing the level of intra and between group correlation for the dependent variable private investment and gross added value related to circular economy sectors in relation to the regression variables persons employed in circular economy sectors, trade in recyclable raw materials, circular material use rate, material flows for circular economy - Sankey diagram data, recycling rate of municipal waste and greenhouse gases emissions from production activities.

The type of model with fixed effects and random effects was evaluated based on the Hausman test whose results allow the use of the model with fixed effects under conditions of high representativeness and statistical significance, as demonstrated by the Chi-square value of the test of 265.738 and p-value (0) lower than the significance level of 0.05.

The fixed effects econometric model equation, which estimates the efficiency of the circular economy through dependent variable PIGVA (private investment and gross value added in circular economy sectors), can be formulated as follows (Equation 1):

$$\text{PIGVA} = \beta0 + \beta1 \cdot \text{TRRM} + \beta2 \cdot \text{GHGE} + \beta3 \cdot \text{RRMW} + \beta4 \cdot \text{CMUR} + \beta5 \cdot \text{PSECE} + \beta6 \cdot \text{MFCE} + \varepsilon \quad (1)$$

Where:

PIGVA – Dependent variable representing private investment and gross value added in circular economy sectors. It measures the efficiency of the transition to the circular economy.

β0 – The constant of the model (intercept). Represents the estimated value of PIGVA when all independent variables are zero. In the fixed effects context, it may vary between groups (Member States), reflecting group-specific characteristics.

β1 – Coefficient associated with trade flows of recyclables (TRRM). Assesses the effect of the number of recycled materials traded between states on PIGVA.

β2 – Coefficient for greenhouse gas emissions *per capita* (GHGE). Indicates the impact of increased pollution on the performance of the circular economy

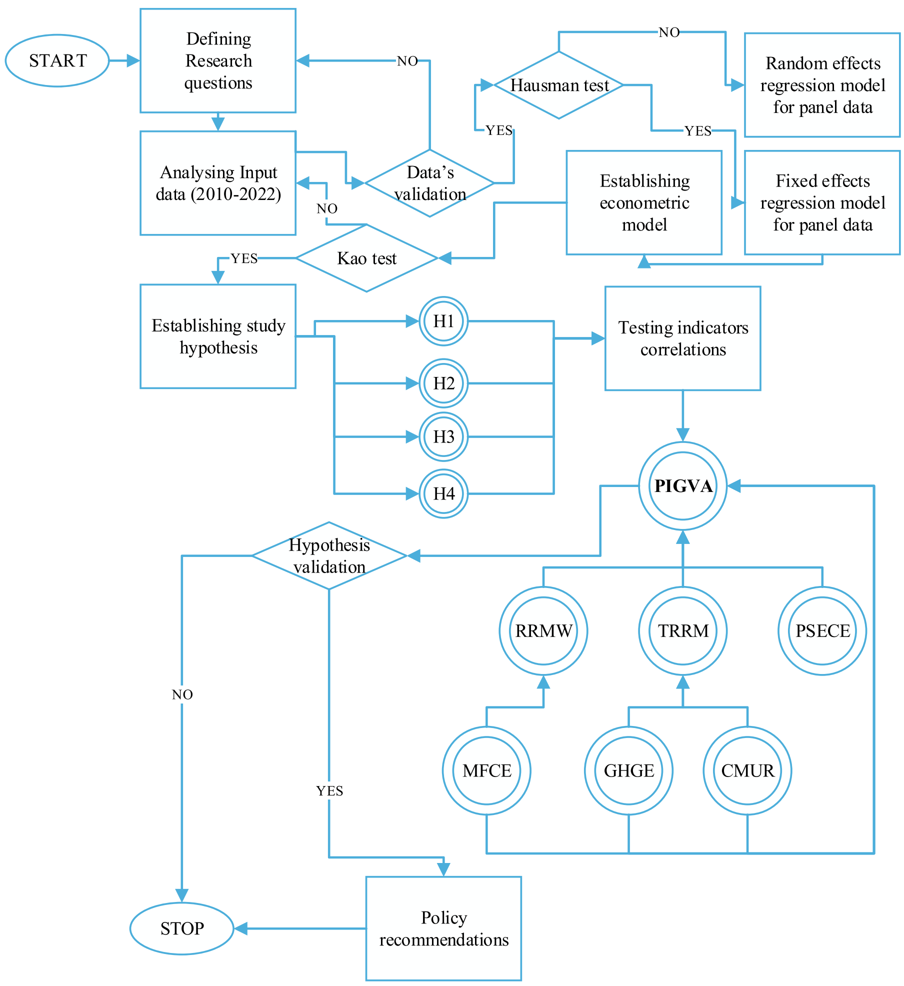


FIGURE 1
Model logic scheme Source: Elaborated by authors.

β3 – Coefficient of the recycling rate of municipal waste (RRMW). Reflects the extent to which increased waste recycling influences investment and gross value added.

β4 – Coefficient of circular material use rate (CMUR). Indicates the impact of utilization of recycled materials to the efficiency of the circular economy

β5 – The coefficient for the number of people employed in circular economy sectors. It measures the attractiveness of the labor market in this sector and its impact on circular economy performance.

β6 – Coefficient for circular material flows. It measures the efficacity of integrating recyclable materials into economic chains and its impact on economic efficiency.

ε – Error (residual) term. Represents the variation in PIGVA that is not explained by the variables included in the model. Captures unknown influences or omitted factors.

## 4 Results

Breusch-Pagan LM test of independence based on 13 complete observations of the panel units has the effect for the 351 degrees of freedom to obtain a good level of independence of the data series and absence of collinearity of the data for a high level of statistical significance Chi-square (351) = 1050.900, Pr = 0.

TABLE 2 Matrix of correlations.

| Variables | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| (1) PIGVA | 1.000 | | | | | | |
| (2) TRRM | 0.598 | 1.000 | | | | | |
| (3) GHGE | −0.108 | 0.023 | 1.000 | | | | |
| (4) RRMW | 0.497 | 0.416 | 0.195 | 1.000 | | | |
| (5) CMUR | 0.508 | 0.608 | 0.153 | 0.518 | 1.000 | | |
| (6) PSECE | 0.803 | 0.648 | −0.177 | 0.306 | 0.367 | 1.000 | |
| (7) MFCE | 0.795 | 0.858 | 0.014 | 0.604 | 0.692 | 0.733 | 1.000 |

Source: Elaborated by the authors using Stata program.

The results of the Modified Wald test for groupwise heteroskedasticity ($chi^2$ (27) = 1.105; Prob > $chi^2$ = 0.0000) allow the rejection of the null hypothesis of equal variance between groups

TABLE 3 Variance inflation factor.

| Variable | VIF | 1/VIF |
|---|---|---|
| MFCE | 8.144 | 0.123 |
| TRRM | 4.096 | 0.244 |
| PSECE | 2.567 | 0.39 |
| CMUR | 2.159 | 0.463 |
| RRMW | 1.874 | 0.534 |
| GHGE | 1.138 | 0.879 |
| Mean VIF | 3.33 | |

Source: Elaborated by the authors using Stata program.

and demonstrate the efficiency of using a regression model with fixed effects.

The efficiency model design was carried out with the multiple regression model applied to panel data using 351 observations collected from Eurostat databases for the period 2010–2022. Observations that capture the evolution of regression indicators both in dynamics and at the regional level. According to the correlation matrix in Table 2 we observe that circular economy efficiency benefits from significant positive correlations with almost all regression indicators (TRRM, CMUR, PSECE and MFCE) which demonstrates that trade and circularity elements capture changes in economic behavior in favor of the transition to circular economy.

In addition, from the correlation matrix table we observe that some variables such as trade in recyclable materials are highly significantly correlated with the circularities of the economy (MFCE) which directly influence the dynamics of the personnel employed in the circular economy sector.

In the context of using a threshold of VIF = 10 to assess multicollinearity in a regression model (O'brien, 2007) the multicollinearity of the variables analyzed in Table 3 was tested.

According to the values presented in Table 3, none of the variables exceeds the threshold of VIF >10, which means that there is no multicollinearity of model data. A fixed effects regression model was developed whose results are presented in Table 4.

The regression results are statistically significant at a representativeness level of 63% according to the coefficient of determination and a regression-like F-test of 91.97 points for 351 degrees of freedom with a high statistical confidence based on the representation of errors below the selected representativeness threshold of 5% (Prob > F equals 0). Also, the model explains 74.54% of the variation between groups (different regions or Member States). Based on the information provided by the Akaike criterion and Bayesian criterion the model has a complex design for a large sample of data, the significance levels allowing prediction for the validation of the primary objective of the efficiency model. Model results show that:

- The positive and significant coefficient of 0.08 obtained for PSECE in the econometric analysis validates hypothesis H1 that increasing employment in circular sectors increases the efficiency of the transition to the circular economy. The analysis of Figure 3 shows that this impact is seasonally differentiated, being influenced by the seasonality of industrial activities and recycling. In economies such as Germany (Kılkış et al., 2023; Oluyisola et al., 2020), with a strong industrial base and well synchronized industrial processes, the seasonality is less pronounced due to the ability to handle constant flows of recycled materials. In contrast, in emerging economies such as Romania (Kwak et al., 2023; Mourão et al., 2024), the processing of collected materials is largely outsourced and seasonality has a more significant impact on labor utilization in the circular sectors. This shows that seasonality can amplify or diminish the impact of employment on gross value added and

TABLE 4 Regression results.

| PIGVA | Coef | St.Err | t-value | p-value | [95% conf | Interval] | Sig |
|---|---|---|---|---|---|---|---|
| TRRM | −0.002 | 0 | −5.04 | 0 | −0.002 | −0.001 | *** |
| GHGE | −0.089 | 0.074 | −1.19 | 0.234 | −0.235 | 0.058 | |
| RRMW | −22.124 | 11.009 | −2.01 | 0.045 | −43.784 | −0.464 | ** |
| CMUR | 46.512 | 34.271 | 1.36 | 0.176 | −20.914 | 113.938 | |
| PSECE | 0.08 | 0.004 | 20.20 | 0 | 0.072 | 0.087 | *** |
| MFCE | 0.807 | 0.237 | 3.40 | 0.001 | 0.34 | 1.274 | *** |
| Constant | −7679.565 | 1152.132 | −6.67 | 0 | −9946.329 | −5412.801 | *** |
| Mean dependent var | | 3369.789 | SD dependent var | | | 5919.733 | |
| R-squared | | 0.634 | Number of obs | | | 351 | |
| F-test | | 91.974 | Prob > F | | | 0.000 | |
| Akaike crit. (AIC) | | 5992.137 | Bayesian crit. (BIC) | | | 6019.163 | |

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: Elaborated by the authors using Stata program.

investment, according to the specific economic context of each Member State (Farghali et al., 2023; Žarković et al., 2022).

- The negative coefficient of −0.0017 for TRRM, statistically significant at $p < 0.001$, highlights the adverse impact of inefficiencies in trade in recyclables on the efficiency of the circular economy. This negative relationship can be explained by challenges associated with managing trade flows, including seasonal variations, logistics costs and trade structures that favor international flows over local processing. From the analysis of Figure 3 for TRRM can be observed, a significant seasonality of recyclables flows. These variations may reflect both the specific dynamics of international markets and the dependence of recycling processes on the seasonality of collection and processing. Thus, during the cold season, collection activities may decrease in certain regions, while industrial demand for recycled materials may remain constant or even increase, thus amplifying pressures on trade chains. Differences between EU Member States in managing these flows become evident depending on the available infrastructure and economic structure. Countries with strong industrial bases and extensive port infrastructures, such as Germany and the Netherlands (European Union, 2024), may report large trade volumes, but a significant part of these flows may represent temporary stocks or intermediate transactions for other countries. In contrast, countries such as Romania (European Commission, 2022; OECD, 2024d), with limited industrial capacity, often export collected recyclables to more developed economies for processing, which reduces the contribution of these flows to domestic gross value added. Consequently, economic policies should aim not only at optimizing trade flows, but also at developing domestic processing capacities and coordination mechanisms at regional level so that the negative impact of trade inefficiencies is mitigated. This would contribute to improving the efficiency of the circular economy across the EU, supporting economic and environmental sustainability objectives.
- As for the Circular Material Use Rate indicator although the coefficient for CMUR (46.512) is not statistically significant ($p = 0.176$) in the analysis in Table 4, the evidence provided by Figure 3 supports the idea that seasonality plays a key role in the dynamics of circular material use. In Member States such as Germany, where the industrial base is strong and production processes are integrated with the use of recycled materials, seasonal variations have less impact due to the ability to handle constant flows of circular materials. Germany (European Environment Agency, 2024; OECD, 2024b), with its robust industrial infrastructure, effectively capitalizes on recycled materials to support domestic demand, thereby contributing to increased investment and gross value added. In contrast, countries such as Romania (European Commission, 2024a; World Bank Group, 2023), with a less developed industrial base, rely heavily on the export of collected materials to economies with advanced industrial infrastructure, such as Germany, for recycling and processing. This multi-stage process, involving collection, export and recovery of materials (including downcycling) (European Commission, 2023a; 2024b; Lingaitiene and Burinskiene, 2024), limits the local impact of circular material use on gross added value. These findings underline the importance of policies to mitigate the effects of seasonality by creating local industrial capacities capable of ensuring a steady and sustainable use of circular resources, thus reducing disparities between EU economies. Hypothesis H3 is therefore validated in a broader context that considers the impact of seasonality on the efficiency of the circular economy.
- In the case of MFCE, the positive coefficient of 0.8073, statistically significant ($p = 0.001$), confirms the validity of hypothesis H4 and the relevance of recyclable material flows in the transition to the circular economy. This demonstrates that the attractiveness of the sector and the integration of recyclable materials into economic processes play a key role in increasing investment and gross value added. The creation of mechanisms to distinguish real from indirect trade flows could be a prerequisite for efficient public policies.

Cointegration tests were designed as shown in Table 5.

TABLE 5 Kao test for cointegration.

| | | |
|---|---|---|
| H0: No cointegration | Number of panels = 27 | |
| Ha: All panels are cointegrated | Number of periods = 11 | |
| Cointegrating vector: Same | | |
| Panel means: Included | Kernel: Bartlett | |
| Time trend: Not included | Lags: 1.63 (Newey-West) | |
| AR parameter: Same | Augmented lags: 1 | |
| | **Statistic** | **p-value** |
| Modified Dickey-Fuller t | −1.2589 | 0.1040 |
| Dickey-Fuller t | −2.0136 | 0.0220 |
| Augmented Dickey-Fuller t | −2.3178 | 0.0102 |
| Unadjusted modified Dickey-Fuller t | −2.9127 | 0.0018 |
| Unadjusted Dickey-Fuller t | −2.9321 | 0.0017 |

Source: Elaborated by the authors using Stata program.

TABLE 6 Descriptive statistics.

| Variable | Obs. | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| PIGVA | 351 | 3369.789 | 5919.733 | 33 | 36978 |
| TRRM | 351 | 1473286.6 | 1904508.2 | 738 | 8890788 |
| GHGE | 351 | 7923.22 | 3066.52 | 3620.33 | 17544.49 |
| RRMW | 351 | 35.594 | 15.678 | 4.1 | 70.3 |
| CMUR | 351 | 8.656 | 6.323 | 0.6 | 29 |
| PSECE | 351 | 137608.42 | 192062.06 | 1643 | 804963 |
| MFCE | 351 | 4537.812 | 5448.23 | 15 | 21733 |

Source: Elaborated by the authors using Stata program.

The Dickey-Fuller tests in Table 5 show significant values ($p < 0.05$ for most of the tests), suggesting the existence of a long-run equilibrium relationship between the variables analyzed, which validates the use of the panel data model to analyze the circular economy.

According to the data obtained by projecting descriptive statistics we observe that the efficiency of the circular economy represented by the composite indicator PIGVA has gradually increased in the period 2010–2022 from 2613 million euro to 4612 million euro as an average across the EU countries. Descriptive statistics are presented in Table 6.

It can be seen from Table 6 that there is a significant level of disparity among European countries in terms of the level of circular economy efficiency, thus countries such as France and Germany record increased levels of circular economy efficiency by up to 6 times the European average (the average value of French circular economy efficiency in the period 2010–2022 was 19819 million euro while that of the German economy was 22194 million euro). At the opposite pole are Cyprus and Malta whose efficiency in terms of implementation of the circular economy does not exceed 110 million euros, which is no more than 3% of the European average. As for trade in recyclable raw materials, during the period under analysis, it increased from 1451610 million tons in 2010–1512009 million tons in 2022, which represents an increase of 4% over the period. The countries with the highest levels of trade in recyclable raw materials are the Netherlands and Spain, whose parameters are up to 5 times higher than the European average, while at the opposite pole the lowest levels of trade in recyclable raw materials are found in Malta and Luxembourg, countries where the amount of recyclable raw materials traded does not exceed 25,000 tons per year on average.

Greenhouse gas emissions have gradually decreased in the European Union as a result of the implementation of environmental protection policies from 8955 kg *per capita* in 2010–7052 kg *per capita* in 2022. The most polluting countries with the highest average levels of greenhouse gas emissions are Denmark (14323 kg *per capita*) followed by Luxembourg (14100 kg *per capita*), which is 80% above the EU average of 7923 kg *per capita*. At the opposite pole, the countries with the lowest pollution levels are Croatia and Sweden, where the pollution level is up to 40% lower than the European average. As regards the recycling rate of municipal waste, a favorable trend can be observed between 2010 and 2022 at European level, from 27.41% in 2010 to 41.33% in 2022. On average the countries with the highest recycling rates are Germany and Austria where the recycling rate reaches up to 66%. At the opposite pole the lowest recycling rates are in Malta 11.92% and Romania 12.65%. The analysis of the rate of circular use of materials shows a favorable evolution at EU level from 7.9% in 2010 to 9.29% in 2022 with the mention that the peak of efficiency of circularity rates was recorded in the pandemic year 2020 when the EU-wide rate was 9.75%.

Among European countries, the highest rates of circularity are recorded in the Netherlands 26.9% and Belgium 18.98%, which is 3 times higher than the European average of 8.66%. At the opposite pole are Ireland (1.82%), Romania (1.98%), Portugal (2.22%) and Greece (2.54%). The level of attractiveness of the sector on the labor market expressed by the dynamics of people employed in the circular economy sectors had a favorable evolution in the period 2010–2022, expressed by an increase of 18% respectively from 127,940 people in 2010 to 151,375 people in 2022. At Member State level, the best represented in terms of the attractiveness of the sector on the labor market are Germany and France, where the population employed in the circular economy sectors is on average 687,324 people (Germany) and 497,102 people in France compared to the European average of 137,608 people. At the opposite pole, the low attractiveness of the labor market in the circular economy sectors is manifested in Luxembourg where only 1926 people are employed annually in circular economy activities and Malta, where 4684 people on average are employed in this field. The growth of the circular economy sector from the perspective of the MFCE indicator is favorable in the period 2010–2022, with the indicator accumulating an 11% increase in the period under analysis from 4262 thousand tons to 4712.59 thousand tons in 2022 (Figure 2).

The structure at the level of each country is characterized by two clusters C1 of the countries with a higher orientation towards the circular economy, consisting of Germany, France, the Netherlands, Belgium, Italy, Spain, Poland and Austria, where the values of the MFCE exceed the multiannual European average and the remaining 19 countries are in the deceleration zone of the circular economy (cluster C2 in Figure 2), where the values of the multiannual averages do not exceed the European average.

The influence of seasonality in the development of the circular economy was analyzed on the basis of the frequency periodograms presented in Figure 3.

According to Figure 3 we observe periodic variation of the variables with respect to frequency which contributes to a better understanding of the seasonal patterns of the dataset. Regarding the efficiency of the circular economy, we notice the seasonal influences of private investment and gross value added in the circular economy which are associated with business cycles, financial flows and the high regional disparity character of the European economy. The efficiency of the circular economy is also reflected in independent indicators on trade in recyclable raw materials that exhibit regional disparities and price influences in the recyclable raw materials market that influence the volume of trade. Greenhouse gas emissions are also influenced by European disparities, with more developed countries tending to pollute the environment more than emerging economies, and in this case a seasonal pattern of emissions is observed, on the one hand related to industrial activity and on the other hand related to variability in the use of energy resources across European countries. Waste reduction through increased recycling rates of municipal waste reflect changes in household consumption and improvements in municipal waste management techniques related to the capacity of each country to implement new circular economy technologies.

The consumption of reusable materials exhibits a cyclical behavior, with seasonality influenced by regional disparities, different demand for circular products across the European Union and the orientation of some countries towards the circular economy (PIGVA seasonal pattern). The attractiveness of the branch for the labor market contains a cyclical pattern influenced by business cycles and seasonality in the demand for jobs under the impact of significant regional disparities observed when studying descriptive statistics. Last but not least the circular economy sector growth indicator exhibits characteristics of periodicity in material flows for the circular economy. These fluctuations are linked to the

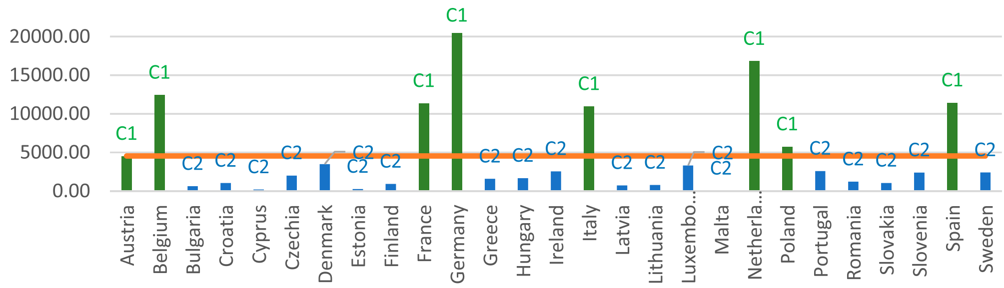


FIGURE 2
Diagram of regional disparities in the growth of the circular economy in the European Union by means of the national average of the MFCE indicator
Source: Elaborated by the authors.

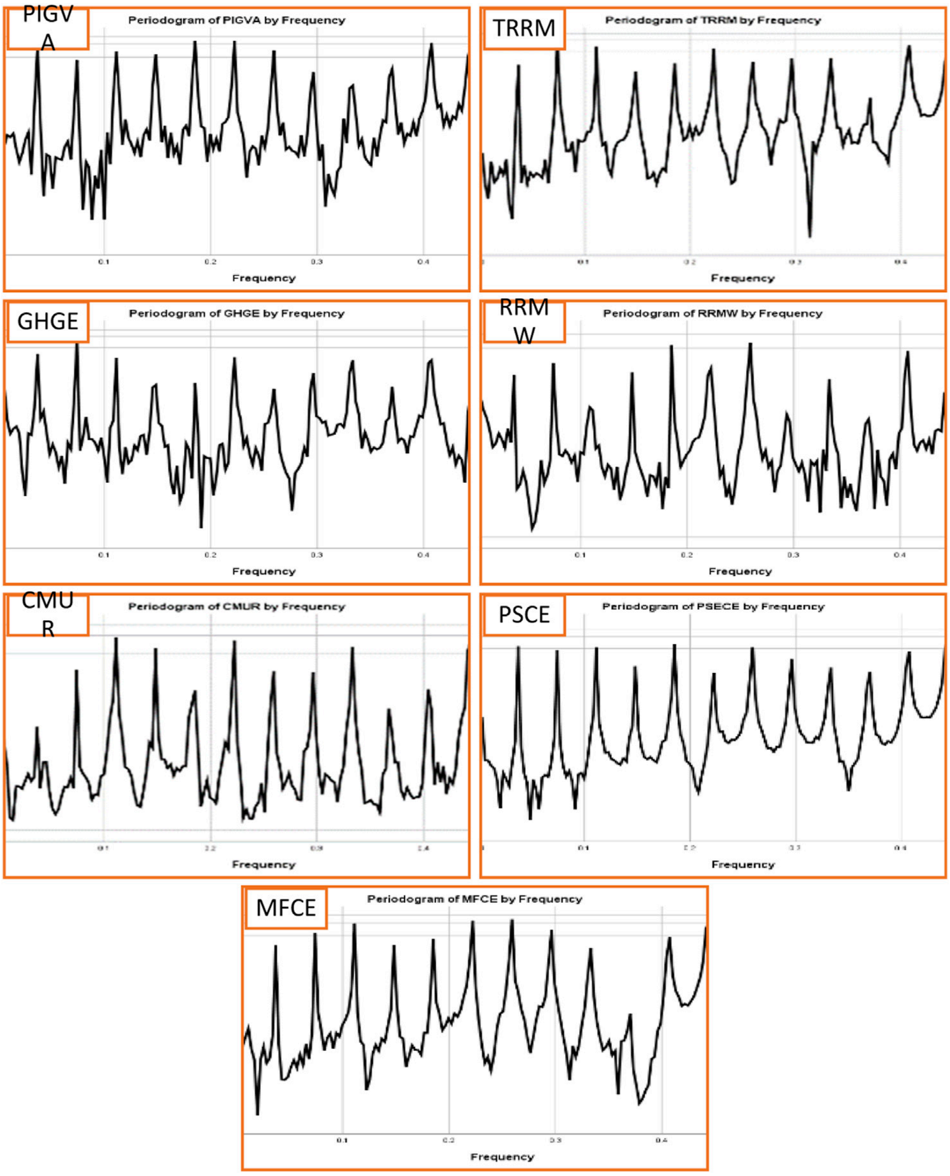


FIGURE 3
Periodograms of analyzed variables according to the frequency identified by spectral analysis.

high level of European circular economy disparities and seasonal factors induced by the nature of industrial demand.

In conclusion, we assess that in terms of public policies it is necessary to seasonally adjust the efficiency by setting up awareness campaigns on the benefits of the circular economy by supporting countries with low efficiency in the circular economy (implementation of dedicated programs to accelerate the circular economy in the 19 countries determined as having a slow circular economy growth (cluster C2 in Figure 2).

## 5 Discussions

The results of the study confirm the validity of all four hypotheses and provide a detailed insight into the dynamics of the transition to the circular economy in the European Union. The econometric analysis demonstrates that the efficiency of this process is fundamentally determined by employment growth in circular economy sectors and the integration of recyclable material flows, these variables having a direct impact on private investment and gross value added. Thus, the study answers the first research question by highlighting that both economic and environmental factors play a key role in optimizing the transition towards circularity. On the one hand, employment and flows of recyclable materials stimulate economic efficiency, while on the other hand, recycling rates and the efficiency of trade in recyclable materials determine the availability and effective use of secondary resources.

As for the second research question, the analysis confirms that private investment and the integration of recyclable materials contribute significantly to improved economic and environmental performance by increasing technological capabilities and reducing dependence on primary resources. These effects in turn lead to a decrease in greenhouse gas emissions and the strengthening of a sustainable economic model capable of generating economic growth through more efficient use of resources and optimized industrial activity. In this respect, the results are fully in line with the literature, which emphasizes the importance of investments in recycling infrastructure and technological innovation to increase circularity. However, the data show significant disparities between Member States, suggesting that the uneven distribution of investments affects the effectiveness of circular economy initiatives.

The third research question focused on analyzing the role of regional disparities and seasonality in the transition to the circular economy. The results show that industrialized regions have greater capacities to recover recyclable materials, which allows them to achieve higher economic output, while less developed economies have to rely on the export of these materials, which reduces local value added. Furthermore, the periodogram analysis reveals that seasonality affects resource availability and recycling processes, creating time inefficiencies that hinder the steady progress of the circular economy. This finding supports the hypothesis that seasonal variations influence the efficiency of circularity, demonstrating the need to implement public policies to mitigate these effects.

With regard to the last research question, the study proposes a series of measures to support a faster and more uniform transition at European level. The econometric results indicate the need to upgrade the municipal recycling infrastructure, as the current systems are not sufficiently cost-efficient, as evidenced by the negative coefficient associated with the recycling rate of municipal waste. Another major area for action is the creation of a single market for recyclable materials at European level, which would help to streamline trade and reduce barriers between Member States. The results of the study also support the implementation of fiscal incentives for private investments in the circular economy, as the analysis has shown that these are essential to increase the efficiency of the sector. Another key issue identified is the need to develop training programs dedicated to circular economy activities, as employment in this sector has been identified as a key determinant of economic performance. In addition, the analysis highlights the importance of strengthening the link between environmental objectives and the performance of the circular economy by tightening product carbon footprint requirements and supporting innovation in recycling of polluting materials.

With these findings, the study validates the four hypotheses initially formulated. First, the analysis confirms that increasing employment in the circular sector increases the efficiency of the transition, as indicated by the positive and significant coefficient of this variable in the econometric model. Second, the results demonstrate that inefficiencies in the trade of recyclable materials negatively affect the performance of the circular economy, a result supported by the negative coefficient of the corresponding variable, which underlines the need to optimize trade flows and develop domestic capacities for processing these materials. Thirdly, the impact of seasonality on the efficiency of the circular economy is confirmed by the periodogram analysis, which highlights significant cyclical fluctuations in trade in recyclables and employment. Finally, the results demonstrate that the attractiveness of the sector and the integration of recyclables into economic processes are key factors for the transition to the circular economy, as indicated by the positive and significant coefficient of recyclables flows.

The analysis highlighted several major aspects of the European circular economy, namely, the sustainability orientation of the circular economy branch still influenced by large regional disparities that hinder the achievement of the Green Deal implementation targets and the transition to climate neutrality. The main obstacles in reaching the targets of transition to circular economy and climate neutrality are: disparities in recycling infrastructure (Kurniawan et al., 2023; Möslinger et al., 2023); technological difficulties in recycling materials, especially plastics, which have proven to be extremely harmful to the environment (Rosenboom et al., 2022; Yang et al., 2023); insufficient investment in the circular economy in some countries (Möslinger et al., 2023; Yang et al., 2023); behavioral barriers and the complexity of supply chains coupled with insufficient use of recycled materials (Kaewunruen et al., 2024; Sharma et al., 2023). Overcoming these barriers requires an integrated approach based on investments in recycling infrastructure, common standards and economic incentives. We believe that the following public policies can increase the efficiency of the circular economy and contribute to improving sustainability at European level.

A first proposed policy aims to modernize the municipal recycling infrastructure by implementing a program to finance from European funds the modernization and expansion of recycling infrastructure (European Commission, 2023c; European Environment Agency, 2023a). The argumentation is based on the results obtained during the implementation of the circular economy efficiency model (Table 4) when the coefficient for the recycling rate of municipal waste was determined to be negative (−22.124) which indicated that the current municipal recycling systems are not sufficiently economically efficient. In order to increase the efficiency of this policy the allocation of funds should be coupled with the implementation of best recycling practices.

The second proposed policy is the creation of a single market for recyclable materials at European level based on common standards for material quality and eliminating trade barriers between Member States (European Union, 2025; Kasznik and Łapniewska, 2023). The rationale for this policy is based on the results of the efficiency model which demonstrated that the dynamics of MFCE material flows and the increase in trade in TTRM recyclable raw materials have a positive relationship with PIGVA. To implement this policy, national regulations on material recycling should be harmonized, a legal framework should be created to facilitate intra-EU transactions for recycled materials and uniform quality standards should be set at EU level.

The third policy aims to introduce tax incentives for private investment in the circular economy. This policy would result in an accelerated transition to the circular economy and ensure a higher level of economic sustainability in the European area (European Commission, 2023a; Eurostat, 2023a; OECD, 2024c). The policy formulation builds on the results of the implementation of the efficiency model showing that private investment (PIGVA) is essential for the performance of the circular economy. This policy can be implemented by instituting tax rebates for companies that allocate significant funds to investments in circular economy projects on the one hand and on the other hand by offering tax deductions for R&D activity in the field of circular technologies.

The fourth policy aims to implement a vocational training program for employment in the circular economy sectors that will result in the creation of specialists with specific skills such as recycling, waste management and sustainable production (European Commission, 2023e; European Economic and Social Committee, 2023). According to the projected efficiency model we observed that there is a direct correlation between the number of people employed in the circular economy and the increase in the economic efficiency of the sector. Thus, it follows that increasing the number of jobs in the circular economy sectors favors a more efficient transition to the circular economy by reducing the skills shortage in the sector. From a practical point of view, this policy can be implemented by launching EU-funded training programs to be implemented through vocational education institutions and companies active in the circular economy. These training programs will be accompanied by the provision of subsidies and training vouchers for workers in traditional industries who would like to retrain for circular economy activities.

The fifth policy aims to strengthen the link between environmental objectives and the performance of the circular economy by tightening requirements for low carbon footprint products and further supporting innovation in recycling of low polluting materials (European Commission, 2023a; 2024b; European Investment Bank, 2023). According to the analysis, it has been observed that the level of emissions still remains a sensitive issue at European level, in particular for developed and industrialized countries where frequent exceedances of the European average are recorded. We appreciate that the practical implementation of carbon footprint product labeling and subsidizing innovation in material recycling will contribute to improving the sustainability of the European economy and effectively protect the environment.

The implementation of these policies, we believe, can ensure a more efficient and faster transition to a circular economy that effectively and efficiently supports the sustainability objectives of the European Union.

This research contributes to the literature by developing an efficiency model of the circular economy that integrates economic, environmental and social variables, providing a comprehensive perspective on the dynamics of this process at the European level. An innovative aspect of the study is the use of seasonality analysis to identify the cyclical patterns of the main variables, thus providing a deeper understanding of how temporal variations influence the transition to the circular economy. Also, the validation of the hypotheses through empirical analysis demonstrates that private investment, flows of recyclables and the attractiveness of the circular sector are key variables for understanding this process. In conclusion, the study makes a significant contribution to the development of public policy strategies and provides clear directions for improving the sustainability of the European economy.

# 6 Conclusion

The study analyzed the transition to circular economy in the European space based on several economic and environmental variables. It used an econometric model based on panel data for the period 2010–2022, the study was carried out at the level of the 27 European Member States.

The study makes a significant contribution to the literature by designing a new efficiency model of the transition to the circular economy that links economic, environmental and social variables for analyzing the European circular economy. The study also highlights regional disparities across Member States and demonstrates that the efficiency of the circular economy depends on the level of infrastructure and policies implemented. The novelty of the research lies in the use of seasonal analysis to identify the cyclical patterns of key variables, thus contributing to the understanding of the dynamics of the European circular economy. At the same time, the validation of the hypotheses through empirical results attests to the importance of private investment of material flows and the attractiveness of the circular sector as defining variables for understanding the transition to the circular economy.

Beyond its academic contributions, this study holds significant practical and policy implications. The findings highlight that achieving an efficient and sustainable circular economy transition requires a multidimensional approach that integrates economic incentives, regulatory alignment, and infrastructure investments. From a policy perspective, the study underscores the importance of developing financial mechanisms to stimulate private investment in circular industries, fostering trade facilitation agreements for recyclable materials, and creating targeted programs to address regional disparities in recycling infrastructure. Furthermore, the study emphasizes the necessity of integrating circular economy objectives into broader environmental strategies, ensuring that emission reduction targets align with circularity goals. By addressing these areas, policymakers can accelerate the transition towards a resilient and resource-efficient European circular economy.

The limitations of the study consist in the impact elements brought by exogenous factors such as economic crises or geopolitical conflict that may induce distortions and are not fully integrated in the model analysis. At the same time, the lack of data related to the variability of emissions may require further analysis to properly capture the relationship between the environment and the circular economy. Another limitation pertains to the use of the trade in recyclable raw materials (TRRM) indicator, which, while relevant, presents methodological challenges. To address this limitation, future research will focus on a more granular evaluation of trade data at the regional level, aiming to identify and mitigate distortions caused by trade flows that are not directly tied to domestic production or consumption. One potential solution involves improving reporting mechanisms to differentiate actual trade flows from transitional or stockpiled materials. Moreover, future studies will delve deeper into understanding regional disparities in the transition to the circular economy. This will include integrating sector-specific data, such as developments in shrinking and textile industries, to identify opportunities for circular transition tailored to sensitive sectors. These opportunities will be subjected to spectral analysis to explore seasonal patterns within these industries, providing further insights into how seasonality impacts the transition to a circular economy.

Our research has shown that the transition to the European circular economy depends on an effective combination of private investment, efficient infrastructure, coordinated public policies and the integration of recyclable material flows. Although there are still significant challenges at the European level the results suggest that addressing these issues through specific policies tailored to the particular context of each Member State can ensure an efficient and sustainable transition to a European circular economy.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

LG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. NB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. VA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. CF: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note



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