

DYNAMICS OF INFLUENCES BETWEEN CIRCULAR ECONOMY, INNOVATION AND SUSTAINABILITY IN THE EUROPEAN UNION USING THE VAR MODEL

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Abstract

This study examines the dynamic relationships between the circular economy, innovation and sustainability in the European Union over the period 2014-2023, using a VAR model to analyze the interactions between municipal waste recycling rates, resource productivity, circular material use rates, environmental tax revenues and R&D expenditure. The results of this study suggest complex relationships between the circular economy, innovation and sustainability in the European Union, highlighting that policies aimed at promoting recycling practices can positively contribute to increasing the use of circular materials. This study emphasizes the importance of integrating public policies in a coherent and complementary way so that circular economy, innovation and fiscal initiatives are effectively coordinated to contribute to a sustainable and equitable transition at European level. Proposed recommendations include the development of innovation strategies that explicitly focus on increasing resource productivity, improving recycling infrastructure and harmonizing the fiscal framework between Member States to support the use of circular materials.

Keywords: *Circular Economy, Innovation, Sustainability, European Union, VAR Model, Public Policy*

Clasificare JEL: *O3, Q56, J88*

1. Introduction and context of the study

In the current global context, characterized by accelerated climate change, dwindling natural resources and increasing economic inequality, the transition to a circular economy has become a priority on the political and economic agenda of the European Union. The circular economy promotes a production and consumption model that optimizes the use of resources, minimizes waste and reduces negative environmental impacts (Kirchherr et al., 2023). The European Green Pact (European Commission, 2023a) and the Circular Economy Strategy (European Commission, 2023b) outlines an ambitious framework aiming to be climate neutral by 2050 and make Europe a global leader in resource efficiency. The role of the circular economy in reducing pressure on natural resources and promoting sustainability is well documented, but the mechanisms through which it interacts with other economic dimensions, such as innovation, are less clearly defined. Investment in research and development (R&D) is essential to develop innovative solutions to

support the transition, and integrating the circular economy with innovation policies can generate significant economic and environmental benefits (Baldassarre, 2025).

Integrating circular economy principles into innovation policies can generate significant economic and environmental benefits by promoting competitiveness, reducing resource dependence and mitigating the negative environmental impacts of economic activities. Despite these potential benefits, major challenges remain, including significant disparities between Member States in terms of access to technological resources, research infrastructure and capacity to implement effective policies. These disparities may hamper progress in achieving a truly circular economy at European level, highlighting the need for coordinated efforts and targeted interventions to address structural differences.

This study aims to investigate the dynamic interactions between indicators of circular economy, innovation and sustainability in the European Union over the period 2013-2023, using a vector autoregressive model (VAR). This methodological approach allows the identification of causal relationships and interdependencies between variables, providing a comprehensive understanding of how policies related to circular economy, innovation and environmental sustainability influence each other over time. By using advanced econometric techniques, this research attempts to fill a gap in the literature by providing empirical evidence on the bidirectional influences between recycling rates, resource productivity, circular materials use, environmental tax revenues and gross domestic expenditure on research and development.

The novelty of this study lies in its integrative approach, which combines circular economy indicators with innovation and sustainability indicators in a single analytical framework. Unlike previous studies that have focused on isolated aspects of the circular economy or innovation, this research examines the interdependencies between multiple indicators, allowing a deeper understanding of how they interact and contribute to broader sustainability goals. In addition, the use of a VAR model allows the identification of both direct and indirect effects, as well as short- and long-term impacts, providing valuable insights into the dynamic nature of these relationships.

The main objectives of the study are:

O1. literature review of the influences between circular economy, innovation and sustainability in the European Union

O2. design the VAR model to investigate the dynamics of influences between circular economy, innovation and sustainability in the European Union

O3. formulation of public policy recommendations

By achieving these objectives, this study aims to provide policy makers with evidence-based recommendations for increasing the effectiveness of circular economy strategies in the European Union. In addition, the findings are expected to contribute to the wider discourse on sustainable development, providing insights that can inform future policy frameworks aimed at promoting innovation, resource efficiency and environmental protection.

2. Literature review

The transition to a circular economy has become a strategic priority for the European Union in the context of growing challenges related to environmental degradation, depletion of natural resources and expanding economic inequalities. The circular economy is promoted not only as a tool for environmental protection, but also as an integrating framework for innovation, competitiveness and social cohesion (Khan et al., 2023; Suchek et al., 2021; Ul-Durar et al., 2023). Research over the last decades has found an increasingly strong link between the circular economy, innovation and sustainability, while emphasizing the complexity of these interactions and the need for a systemic approach (Brglez et al., 2024; Kuzma et al., 2022; Rios et al., 2022). This thematic convergence reflects a paradigm shift in economic and environmental thinking, in which innovation processes are central to achieving circularity and sustainable development goals.

The circular economy has evolved considerably, moving beyond its original framework, limited to recycling and waste management, to become an economic paradigm oriented towards resource regeneration and minimizing the environmental impacts of human activities. In a comprehensive analysis of 221 definitions of the circular economy, Kirchherr et al. (Kirchherr et al., 2023) highlights the multidimensional nature of this concept, which brings together environmental, economic and social objectives in a coherent vision of sustainable development. This approach is reflected in the European Green Pact (European Commission, 2023a) and the Circular Economy Action Plan (European Commission, 2023b), setting ambitious targets for climate neutrality and resource efficiency by 2050.

Recent expert studies (Baldassarre, 2025; Kandpal et al., 2024; Morelli et al., 2024) emphasizes that the circular economy is not limited to technological solutions, but implies a profound transformation of production and consumption patterns as well as economic governance paradigms. Value creation is no longer seen solely through the prism of economic efficiency, but also by closing material life cycles, reducing negative externalities and integrating sustainability into decision-making.

Innovation is a key pillar in facilitating the transition towards circular economic models. Empirical research underlines the importance of eco-innovation, technological progress and investment in research and development (R&D) in supporting circular practices. García-Valderrama et al. (García-Valderrama et al., 2024) demonstrates that firms that adopt eco-innovation strategies are more likely to implement resource efficiency, reuse and remanufacturing measures. Technological innovation also facilitates the development of advanced recycling technologies, digital material tracking tools and service and circularity-based business models.

In EU policies, the link between innovation and the circular economy is becoming increasingly clear. Programs such as Horizon Europe (European Commission, 2024) include explicit sustainability and circular economy objectives, fostering the integration of resource efficiency, digital economy and climate neutrality themes. Perotti et al. (Perotti et al., 2025) argues that innovation strategies need to be aligned with the objectives of the circular economy in order to generate sustainable systemic change.

Empirical analysis by Malatyinszki, Zéman and Kálmán (Malatyinszki et al., 2025), respectively (Skare et al., 2024), demonstrates a positive correlation between R&D investment and the rate of circular materials use and resource productivity. These findings underline the need for cross-cutting policies that support knowledge transfer, cross-sectoral collaboration and support for innovation in SMEs.

The link between the circular economy and sustainability is well documented, particularly from the perspective of reducing negative environmental impacts. However, some literature draws attention to potential tensions between the environmental, economic and social dimensions of sustainable development. Authors Zavos, Lehtokunnas and Pyyhtinen (Zavos et al., 2024) warns that a strictly technocratic implementation of the circular economy, lacking social and territorial anchoring, may generate inequalities and exclude vulnerable actors from the transition process.

Mainstreaming the circular economy into sustainability strategies requires a holistic approach, including social equity, just transition and participation of local actors. Some studies (Deserno & Sterk, 2024; Dincă et al., 2022; Rodríguez-Antón et al., 2022) argue that the circular economy goals need to be linked to those of the 2030 Agenda, and indicators such as resource productivity, material circularity or green tax revenues can provide robust measures of progress in this regard.

Green fiscal policies are another important channel for influencing economic behavior and resource allocation. A number of studies (Abbas et al., 2024; Sharif et al., 2023; Zhang et al., 2023) emphasize the potential of environmental taxes to correct negative externalities and stimulate the circular transition, but also draw attention to the risk that these instruments may be ineffective in the absence of consistent and fair implementation.

The empirical literature on the relationships between circular economy, innovation and sustainability in the EU is growing but remains heterogeneous. Some studies have used panel regression or structural models to estimate the long-term effects of circular policies on economic and environmental performance (Nguyen et al., 2024; Pan et al., 2024; Tiwari & Si Mohammed, 2024). Authors Satrovic, Zafar and Suntraruk (Satrovic et al., 2024) have shown that environmental policy intensity and innovative capacity are positively associated with environmental performance and green competitiveness in EU Member States.

In a more recent approach Adam, Abednego and Aboagye (Adam et al., 2025), used firm-level data to show that circular business models based on product life extension are positively correlated with innovative output. Mejía Ochoa et al. (Mejía Ochoa et al., 2024), in a meta-analysis of case studies on the implementation of the circular economy in Europe, identifies technological innovation, legislative support and cooperation between stakeholders as key success factors.

Application of dynamic econometric models such as the VAR model (Holmen et al., 2025; Wang et al., 2024), provides an innovative perspective on the inter-relationships between indicators of circular economy, innovation and sustainability. These models make it possible to capture bidirectional influences and lagged effects between variables such as waste recycling rates, R&D expenditure or green tax revenues, providing a thorough understanding of the mechanisms of influence over time.

Although the European Union promotes a common framework for the transition to a circular economy, there are significant differences in recycling, innovation and sustainability performance between Member States. Data provided by Eurostat (Eurostat, 2024a) highlights that countries such as the Netherlands, Germany, Belgium or Sweden have high rates of circular material use and consistent levels of resource productivity, while Central and Eastern European countries (Romania, Bulgaria, Croatia) face systemic delays due to underdeveloped infrastructure, low investment in research and a fragile institutional framework.

These disparities reflect not only economic gaps, but also differences in political culture, strategic priorities and administrative capacity to implement public policies. Authors Nijkamp et al., Bourdin and Torre, Kanda et al., (Bourdin & Torre, 2025; Kanda et al., 2025; Nijkamp et al., 2024) argues that the success of the transition to a circular economy depends to a large extent on coherence and institutional capacity at national level, suggesting that one-size-fits-all approaches may fail in the absence of adaptations to the local context.

Moreover, environmental and innovation policies are rarely integrated in a coherent way. For example, in some Member States, subsidies to traditional, resource-intensive sectors can cancel out the positive effects of environmental taxes or policies promoting eco-innovation (Brusselsaers & Gillabel, 2024; Chanal et al., 2025). Raportul Agenției Europene de Mediu (EEA, 2024) emphasizes the urgent need to align economic instruments - such as taxes, subsidies and public procurement - with circular economy objectives to avoid inconsistencies that undermine the effectiveness of public policies.

This lack of coherence is also highlighted by various studies (Agovino et al., 2024; Chioatto & Sospiro, 2023; De Pascale et al., 2023), which draw attention to the fact that many Member States lack a clear legislative framework for implementing circular economy principles in innovation or industrial development strategies. In the absence of an integrated vision and inter-institutional coordination mechanisms, the risk is that circular policies remain fragmented and inefficient.

At the same time, the level of investment in research and development varies considerably between Member States, affecting their capacity to generate and adopt sustainable innovations. Countries such as Germany, Sweden and Finland invest significantly in research and development, while Romania and Bulgaria allocate much more modest resources to this area, according to Eurostat (Eurostat, 2024c). These differences directly influence the capacity of productive systems to innovate as well as the potential for transition to circular models.

The transition to an innovation-driven circular economy is not without challenges. First, systemic barriers persist linked to the economic structure of some Member States, where resource-intensive extraction and processing industries are at the core. This limits the ability of these economies to rapidly adopt circular and innovative models without affecting labor market stability or industrial competitiveness. According to the authors Rodríguez-Pose and Bartalucci (Rodríguez-Pose & Bartalucci, 2024) and Fratesi (Fratesi, 2025), the circular transition risks exacerbating regional inequalities unless accompanied by support measures for disadvantaged regions and vulnerable sectors.

Second, the lack of clear regulatory frameworks and fiscal incentives dedicated to circular innovation hampers the widespread adoption of these models. Authors' studies Bhavsar, Sridharan and Sudarsa (Bhavsar et al., 2023) indicates that, in many cases, circularity-oriented innovation is discouraged by lack of access to finance, unclear regulations on reuse of materials or lack of uniform standards for the quality of recycled materials.

Another major obstacle is related to consumer behaviour and organizational culture within companies. Even in developed countries, reluctance towards reused products, lack of confidence in their sustainability or a preference for linear consumption patterns continue to limit demand for circular solutions (Abbate et al., 2023; Levänen et al., 2023). In this respect, public policies should include educational and awareness-raising components aimed at changing consumer perceptions and behavior.

Finally, the transition to a circular economy underpinned by innovation also requires an effort to reform the paradigms for assessing economic performance. Traditional indicators such as GDP do not reflect progress in circularity or sustainability. There is a need to develop integrated monitoring frameworks, including indicators such as circular material use rates, resource intensity, impacts on biodiversity and contribution to climate targets.

Although the literature on circular economy, innovation and sustainability has expanded significantly, there are still conceptual and empirical gaps that need to be addressed. First, longitudinal studies investigating the long-term effects of circular policies on innovation and resource efficiency are needed, as most existing research uses short time-series data or static models. Panel-VAR studies or dynamic ARDL models can contribute significantly to understanding these complex relationships.

Second, the literature is relatively poor in analyses that integrate the social dimensions of the circular transition. Issues such as social equity, employment impacts, digital exclusion, or unequal access to innovation are rarely integrated into theoretical or empirical models. Future research should include these dimensions to assess to what extent the transition is truly inclusive and socially sustainable.

Further analysis at sectoral and national level is also needed to capture the particularities of the transition in specific industries (e.g. construction, textiles, electronics) and in countries with different institutional and economic contexts. Comparative studies between EU Member States can highlight good practices and enablers of the circular transition and help to formulate policies tailored to local contexts. Last but not least, the integration of advanced modeling tools - such as dynamic dynamic general equilibrium (DSGE) models, multi-agent simulations or complex network analysis - can provide a more detailed understanding of the interdependence, emergence and feedback effects between the circular economy, innovation and sustainability. These approaches allow simulating alternative public policy scenarios and assessing their systemic impacts.

The literature review has made it very clear that the circular economy, innovation and sustainability need to be addressed in an integrated and coordinated manner, both in theory and in terms of public policy design and implementation. The European Union provides an ambitious framework for this transition, but its success depends significantly on the ability of Member States

to reduce disparities, stimulate circularity-oriented innovation and promote coherent fiscal and education policies.

At the same time, future research must go beyond sectoral or isolated approaches and adopt systemic, interdisciplinary and equity-oriented perspectives to support a sustainable, resilient and inclusive transition.

3. Method

The methodology of this study aims to investigate the dynamics of the influences between circular economy, innovation and sustainability in the European Union by applying a Vector Autoregressive (VAR) model. The choice of the VAR model is based on its ability to capture the dynamic relationships and interdependencies between the selected variables, providing a comprehensive perspective on how circular economy and innovation policies and initiatives contribute to sustainability goals.

The analysis is based on a panel dataset covering the period 2014-2023, collected at EU level for all Member States from official sources available through the Eurostat database. The indicators included in the study have been selected to reflect the relevant aspects of circular economy, innovation and economic and environmental sustainability as shown in Table 1.

Table no. 1 Presentation of indicators

Indicators	Symbol	U.M.	Source
Recycling rate of municipal waste	RECWAST	%	Eurostat (Eurostat, 2025b)
Resource productivity	RPROD	Euro per kilogram	Eurostat (Eurostat, 2024d)
Circular material use rate	MATUSER	%	Eurostat (Eurostat, 2024a)
Environmental tax revenues	ENVT	Percentage of gross domestic product (GDP)	Eurostat (Eurostat, 2025a)
Gross domestic expenditure on R&D	GDRD	Percentage of gross domestic product (GDP)	Eurostat (Eurostat, 2024b)

Source: Elaborated by the authors based on Eurostat data

Thus, the recycling rate of municipal waste (RECWAST), expressed as a percentage, measures the proportion of recycled waste as a proportion of total waste generated and is a key indicator for assessing progress towards a circular economy. Resource Productivity (RPROD), expressed in euros per kilogram, indicates the efficiency of resource use in an economy and is both economically and environmentally relevant, with the potential to demonstrate a more responsible and sustainable use of natural resources. The Material Use of Circular Materials Utilization Rate (MATUSER), expressed as a percentage, measures the proportion of materials that are reintroduced into the economic process through recycling, giving a clear picture of the degree to which economic cycles are closed. Revenues from environmental taxes (ENVT), expressed as a percentage of gross domestic product (GDP), provide a measure of the contribution of fiscal policies to achieving sustainability objectives, reflecting the effectiveness of economic instruments to reduce environmental impacts. Gross Domestic Expenditure on Research and Development (GERD), also expressed as a percentage of GDP, is a key indicator of innovation efforts and is essential for assessing progress in the development of sustainable technologies and processes.

The VAR model applied in this research allows a bidirectional analysis of the influences between the selected indicators, allowing both short-run and long-run effects to be examined. In this model, each variable is explained by its own lagged values and by the lagged values of the other variables, allowing the identification of complex dynamic relationships and possible feedback effects. The aim of this methodology is to identify not only direct effects between the selected indicators, but also indirect influences and possible causal relationships, thus contributing to a

better understanding of how the circular economy and innovation can support sustainability objectives in the context of the European Union.

The VAR model applied in this research includes five endogenous variables: recycling rate of municipal waste (RECWAST), resource productivity (RPROD), circular materials use rate (MATUSER), environmental tax revenues (ENVT) and gross domestic expenditure on research and development (GDRD). Each variable is explained by its own lagged values and the lagged values of the other variables, using a lag of order 1.

The VAR model equations are expressed as:

1. Equation for the recycling rate of municipal waste (RECWAST):

$$RECWAST_t = f(RECWAST_{t-1}, RPROD_{t-1}, MATUSER_{t-1}, ENVT_{t-1}, GDRD_{t-1}) + \varepsilon_{RECWAST,t} \quad (1)$$

2. Equation for the resource productivity (RPROD):

$$RPROD_t = f(RECWAST_{t-1}, RPROD_{t-1}, MATUSER_{t-1}, ENVT_{t-1}, GDRD_{t-1}) + \varepsilon_{RPROD,t} \quad (2)$$

3. Equation for circular material use rate (MATUSER):

$$MATUSER_t = f(RECWAST_{t-1}, RPROD_{t-1}, MATUSER_{t-1}, ENVT_{t-1}, GDRD_{t-1}) + \varepsilon_{MATUSER,t} \quad (3)$$

4. Equation for revenues from environmental taxes (ENVT):

$$ENVT_t = f(RECWAST_{t-1}, RPROD_{t-1}, MATUSER_{t-1}, ENVT_{t-1}, GDRD_{t-1}) + \varepsilon_{ENVT,t} \quad (4)$$

5. Equation for gross domestic expenditure on research and development (GERD):

$$GDRD_t = f(RECWAST_{t-1}, RPROD_{t-1}, MATUSER_{t-1}, ENVT_{t-1}, GDRD_{t-1}) + \varepsilon_{GDRD,t} \quad (5)$$

Where,

t is the current year and t-1 is the previous year.

$\varepsilon_{Variable,t}$ represent the error terms for each equation, capturing unobserved components and specification errors.

These equations reflect the fact that each indicator is determined not only by its previous values but also by the previous values of the other variables in the model. This structure allows two-way analysis of the influences between indicators, including the identification of short-run and long-run effects as well as possible causal relationships.

Taking into account the European Union strategies and the dynamic relationships between the analyzed variables in the period 2014-2023, we formulate the following research hypotheses, which can be validated based on the results obtained from the VAR model:

Hypothesis 1 (H1): An increase in the recycling rate of municipal waste (RECWAST) leads to a significant increase in the rate of use of circular materials (MATUSER) in the European Union, reflecting the effectiveness of the circular economy strategies promoted by the Action Plan for the Circular Economy.

Hypothesis 2 (H2): Revenues from environmental taxes (ENVT) do not have a significant negative impact on resource productivity (RPROD), suggesting that environmentally oriented fiscal policies do not negatively affect resource use efficiency in the European Union.

These hypotheses will be tested through the application of the VAR model, which allows the identification of reciprocal influences between indicators and the measurement of their impact in the short and long run.

4. Results and Discussion

This section analyzes the complexity of the dynamic relationships between municipal waste recycling rates, resource productivity, circular material use rates, environmental tax revenues and R&D expenditure in the context of the European Union's efforts to implement comprehensive strategies to support the transition towards a circular and sustainable economy. The analysis aims to assess the extent to which these interrelated variables align with the ambitious targets set by initiatives such as the European Ecological Pact, which aims to be climate neutral by 2050, the Action Plan for the Circular Economy, which aims to optimize resource use and minimize waste, and the Innovation and Sustainability Strategy, which promotes R&D investments to boost technological innovation and resource efficiency in all EU Member States over the period 2014-2023.

Vector autoregression model results are presented in Table 2.

Table no. 2. Vector autoregression

Sample: 2014 thru 2023			Number of obs = 10			
Log likelihood = 251.5531			AIC = -44.31062			
FPE = 9.96e-26			HQIC = -45.30643			
Det(Sigma ml) = 9.73e-29			SBIC = -43.40287			
Equation	Parms	RMSE	R-sq	Chi2	P>chi2	
RECWAST	6	0.785393	0.9780	444.4194	0.0000	
RPROD	6	0.04690	0.9765	414.8366	0.0000	
MATUSER	6	0.228111	0.9678	300.1703	0.0000	
ENVT	6	0.034547	0.9893	923.5125	0.0000	
GDRD	6	0.048566	0.8465	55.16164	0.0000	
Variable	Coefficient	Std.	err.	z	P>z	[95% conf. interval]
RECWAST						
RECWAST						
L1.	0.608	0.197	3.080	0.002	0.221	0.994
RPROD						
L1.	16.558	7.610	2.180	0.030	1.643	31.474
MATUSER						
L1.	-1.056	1.966	-0.540	0.591	-4.909	2.798
ENVT						
L1.	1.411	11.759	0.120	0.904	-21.635	24.458
GDRD						
L1.	-2.564	7.518	-0.340	0.733	-17.300	12.171
cons	-4.716	60.513	-0.080	0.938	-123.319	113.886
RPROD						
RECWAST						
L1.	-0.013	0.012	-1.100	0.271	-0.036	0.010
RPROD						
L1.	0.928	0.455	2.040	0.041	0.037	1.819
MATUSER						
L1.	0.207	0.117	1.760	0.078	-0.023	0.437
ENVT						
L1.	0.049	0.702	0.070	0.944	-1.327	1.425
GDRD						
L1.	-0.697	0.449	-1.550	0.121	-1.577	0.183
cons	-0.169	3.614	-0.050	0.963	-7.252	6.915
MATUSER						
RECWAST						
L1.	0.140	0.057	2.450	0.014	0.028	0.252
RPROD						
L1.	-1.103	2.210	-0.500	0.618	-5.436	3.229
MATUSER						
L1.	0.352	0.571	0.620	0.538	-0.767	1.471

ENVT						
L1.	-0.289	3.415	-0.080	0.933	-6.982	6.405
GDRD						
L1.	2.974	2.184	1.360	0.173	-1.305	7.254
cons	-1.206	17.575	-0.070	0.945	-35.653	33.241
ENVT						
RECWAST						
L1.	0.013	0.009	1.470	0.140	-0.004	0.030
RPROD						
L1.	-0.826	0.335	-2.470	0.014	-1.482	-0.170
MATUSER						
L1.	-0.328	0.086	-3.790	0.000	-0.498	-0.159
ENVT						
L1.	-0.880	0.517	-1.700	0.089	-1.894	0.133
GDRD						
L1.	-0.510	0.331	-1.540	0.123	-1.158	0.138
cons	9.837	2.662	3.700	0.000	4.620	15.054
GDRD						
RECWAST						
L1.	0.007	0.012	0.590	0.554	-0.017	0.031
RPROD						
L1.	0.116	0.471	0.250	0.805	-0.806	1.038
MATUSER						
L1.	0.102	0.122	0.840	0.404	-0.137	0.340
ENVT						
L1.	0.699	0.727	0.960	0.336	-0.726	2.124
GDRD						
L1.	1.000	0.465	2.150	0.031	0.089	1.911
cons	-3.259	3.742	-0.870	0.384	-10.593	4.075

Source: Elaborated by the authors using Stata 18

The results obtained from the application of the VAR model indicate a high statistical significance of the relationships analyzed, demonstrated by the high values of the coefficient of determination R² for each equation, namely 0.9780 for RECWAST, 0.9765 for RPROD, 0.9678 for MATUSER, 0.9893 for ENVT and 0.8465 for GDRD. These high values suggest an excellent ability of the model to explain the variations of the analyzed indicators over the period 2014-2023. The Chi-Square test, applied for each equation, also indicates a strong statistical significance, all P-values being equal to 0.0000, confirming the validity of the estimates and the adequacy of the model to the analyzed data.

The validation of the hypotheses formulated based on the results of the VAR model reveals statistically significant relationships between some of the indicators analyzed. Regarding the first hypothesis, which states that an increase in the recycling rate of municipal waste leads to a significant increase in the utilization rate of circular materials in the European Union, the results indicate a positive coefficient of 0.140 for the RECWAST variable in the equation for MATUSER, with a p-value of 0.014. The high statistical significance of this coefficient, below the conventional threshold of 0.05, suggests a significant positive relationship between the two indicators, indicating that measures to stimulate recycling do indeed contribute to an increase in the utilization rate of circular materials. This result validates the first hypothesis and confirms the effectiveness of the circular economy strategies promoted by the Circular Economy Action Plan.

In the case of the second hypothesis, that revenues from environmental taxes do not have a significant negative impact on resource productivity, the results provided by the VAR model support this hypothesis. The coefficient of the ENVT variable in the equation for RPROD has a positive value of 0.049, but statistically insignificant with an extremely high p-value of 0.944. The lack of statistical significance suggests that environmentally oriented fiscal policies do not have a negative impact on resource use efficiency in the European Union. In addition, the fact that the sign of the coefficient is positive, albeit insignificant, may suggest that environmental fiscal policies

may even contribute to some extent to resource use efficiency. The result of this test validates the hypothesis, indicating that environmental fiscal policies do not exert a significant negative effect on resource productivity.

The results of the VAR model validate the two hypotheses formulated, suggesting that an increase in the recycling rate of municipal waste contributes positively and significantly to an increase in the utilization rate of circular materials, while environmental fiscal policies do not negatively affect resource productivity.

The results of the Granger causality tests as shown in Table 3 provide valuable insight into the directions of influence between the variables analyzed in the VAR model. Granger-Causality tests examine whether the past values of one variable contribute significantly to explaining the present variations of another variable. A significant result indicates a Granger causality relationship, which suggests that one variable predictively influences another variable.

Table no. 3. Granger causality Wald tests

Equation	Excluded	chi2	df	Prob>Chi2
RECWAST	RPROD	4.734	1	0.030
RECWAST	MATUSER	0.288	1	0.591
RECWAST	ENVT	0.014	1	0.904
RECWAST	GDRD	0.116	1	0.733
RECWAST	ALL	9.358	4	0.053
RPROD	RECWAST	1.211	1	0.271
RPROD	MATUSER	3.104	1	0.078
RPROD	ENVT	0.005	1	0.944
RPROD	GDRD	2.410	1	0.121
RPROD	ALL	16.598	4	0.002
MATUSER	RECWAST	5.981	1	0.014
MATUSER	RPROD	0.249	1	0.618
MATUSER	ENVT	0.007	1	0.933
MATUSER	GDRD	1.855	1	0.173
MATUSER	ALL	21.345	4	0.000
ENVT	RECWAST	2.175	1	0.140
ENVT	RPROD	6.089	1	0.014
ENVT	MATUSER	14.397	1	0.000
ENVT	GDRD	2.378	1	0.123
ENVT	ALL	36.327	4	0.000
GDRD	RECWAST	0.350	1	0.554

GDRD	RPROD	0.061	1	0.805
GDRD	MATUSER	0.697	1	0.404
GDRD	ENVT	0.925	1	0.336
GDRD	ALL	7.463	4	0.113

Source: Elaborated by the authors using Stata 18

The results of the Granger causality tests provide a clear insight into the dynamics of the analyzed indicators at the level of the EU Member States and how they interact in the context of the implementation of circular economy, innovation and green tax strategies. The impact of these results at European country level can be analyzed on the basis of the significant relationships identified between the indicators.

As regards the relationship between resource productivity and municipal waste recycling rate, the model results indicate a significant causality from resource productivity to recycling with a p-value of 0.030. This suggests that in European countries, increased resource use efficiency contributes to improved recycling practices, probably due to integrated policies that aim at both optimizing resource use and increasing recycling rates. This is relevant for countries that are investing in the efficiency of industrial processes and adopting innovative technologies, thus having a positive impact on municipal waste recycling capacity. In particular, countries that have implemented coherent circular economy strategies, such as Germany, the Netherlands and the Nordic countries, could benefit most from these synergies.

In the case of the relationship between the recycling rate of municipal waste and the utilization rate of circular materials, the results indicate a strong and significant (p-value = 0.014) relationship between the two variables. This result suggests that in European countries, improved recycling capacities directly contribute to increased use of circular materials in economic processes, which is in line with the objectives of the Circular Economy Action Plan. This relationship is essential for Member States wishing to increase their resource efficiency and reduce their dependence on primary resources. For example, countries with well-developed waste management infrastructures, such as Belgium and Sweden, are likely to make greater progress in using recycled materials.

The relationship between resource productivity and environmental tax revenues, although statistically significant (p-value = 0.014), shows a negative coefficient, indicating that increased resource use efficiency may lead to a decrease in environmental tax revenues. At the Member State level, this result suggests that resource efficiency policies may have unintended effects on tax revenues from the taxation of polluting activities. In particular, countries with tax systems heavily dependent on environmental taxes, such as Denmark and Finland, could be negatively affected in the long run if improvements in resource efficiency are not accompanied by appropriate adjustments in tax policies. In this context, Member States need to balance sustainability objectives with the need to maintain the tax revenues needed to finance the green transition.

The significant causality identified between the rate of circular materials use and environmental tax revenues (p-value = 0.000) indicates that an increase in the use of circular materials has a negative effect on tax revenues from the taxation of polluting activities. This relationship can be explained by the fact that higher use of circular materials reduces the demand for primary resources and, hence, the environmentally negative activities that are taxed. At the level of European countries, this result suggests that policies promoting the use of circular materials need to be supported by an adapted fiscal framework to avoid a possible decrease in tax revenues from environmental taxes. For example, countries with ambitious programs to promote the circular economy, such as the Netherlands, may need to explore new sources of green tax revenues to support their sustainability policies.

On the other hand, the results indicate that none of the variables analyzed has a significant effect on R&D expenditure (GDRD), with all p-values being well above the conventional

significance threshold of 0.05. This suggests that in the European Union, R&D investments are not directly influenced by environmental fiscal policies, resource use efficiency or recycling and circular material utilization rates. This result can be explained by the fact that R&D investments are more likely to be influenced by national policy priorities, European Structural Funds or industry-specific factors. In particular, countries allocating significant R&D budgets, such as Germany and France, might be less affected by exogenous influences stemming from circular economy policies or green taxation.

The results of the Granger causality tests suggest that EU Member States can benefit from synergies between recycling policies, the use of circular materials and resource efficiency. However, there is a risk that improvements in resource efficiency could reduce revenues from environmental taxes, which could affect the ability of states to finance the transition to a circular economy. In this respect, European countries need to pay particular attention to balancing these objectives through integrated policies, combining measures to stimulate the circular economy with tailored tax reforms.

Figure 1 presents the results of the analysis of impulse response functions (IRFs) obtained from the reduced VAR model, showing the impact of an unexpected increase (impulse) in the variable RECWAST (municipal waste recycling rate) on the variables ENVT (environmental tax revenues), GDRD (research and development expenditures), MATUSER (circular materials use rate) and RPROD (resource productivity) over a 10-step period (years). The 95% confidence intervals are represented by gray bands and the response functions are illustrated by blue lines.

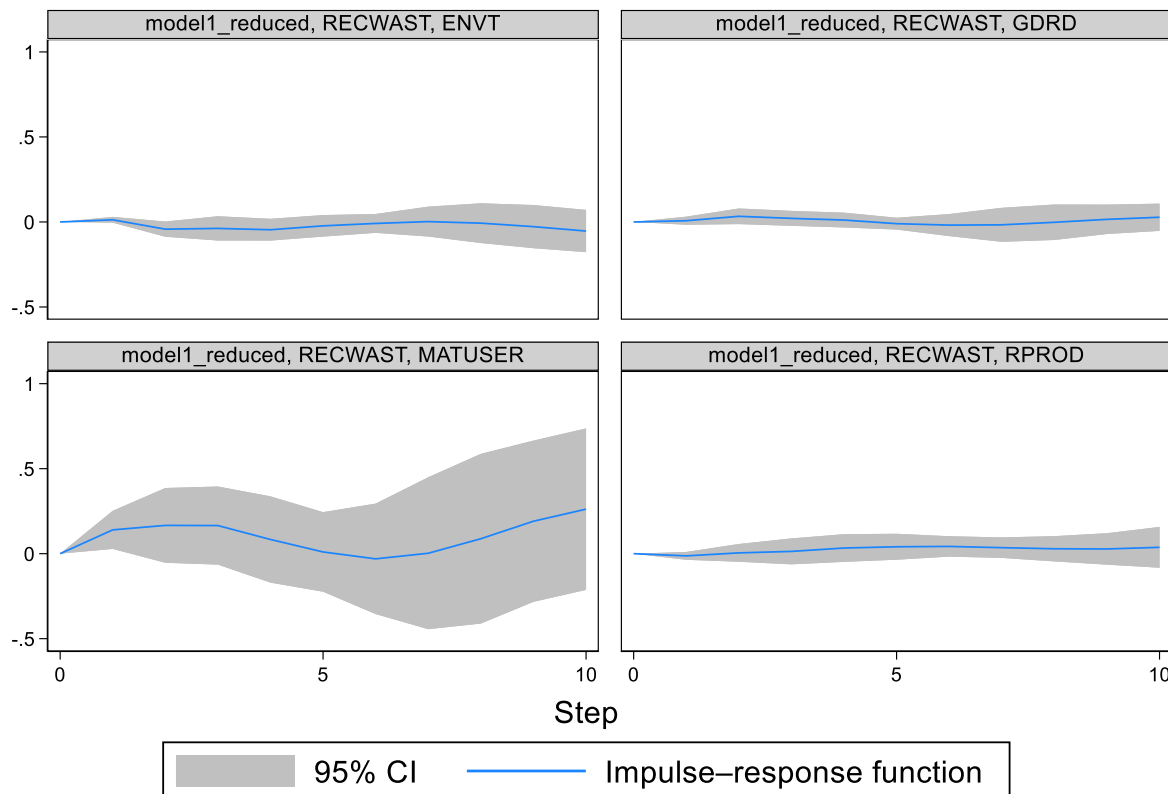


Figure no. 1. Impulse Response Functions (IRFs) for the RECWAST variable over ENVT, GDRD, MATUSER and RPROD variables

Source: Elaborated by the authors using Stata 18 program

The results indicate that the impact of an unexpected increase in the recycling rate of municipal waste on environmental tax revenues remains close to zero over the entire period analyzed, suggesting a statistically insignificant relationship. This finding is supported by the relatively narrow confidence intervals, which include zero, indicating that recycling policies do not

produce substantial effects on environmental tax revenues, most likely due to the fact that environmental tax revenues are predominantly related to polluting activities that are not directly influenced by the recycling process.

In terms of R&D expenditure, the results suggest an insignificant effect of an increase in the municipal waste recycling rate on this variable. The response function remains constant and close to zero over the entire period analyzed, and the confidence intervals consistently include zero. This result suggests that R&D investments within the EU Member States are driven by factors other than improvements in the recycling rate, such as national innovation priorities, European Structural Funds or strategic initiatives in high value-added economic sectors.

In contrast, the impact of an unexpected increase in the recycling rate of municipal waste on the rate of use of circular materials proves to be positive and significant in the long run. The response function shows a clear increasing trend after the first few steps, indicating a positive relationship between municipal waste recycling and the use of circular materials. This finding is consistent with previous results from the VAR model and Granger causality tests, which indicated a significant relationship between these indicators. In particular, this result suggests that policies that promote recycling effectively contribute to the integration of recycled materials into economic processes, which is essential for achieving the goals set by the Circular Economy Action Plan.

The analysis of the impact of an unexpected increase in the municipal waste recycling rate on resource productivity indicates an insignificant relationship, with the response function being almost constant and close to zero over the entire period analyzed. The relatively wide confidence intervals suggest uncertainty in estimating the effects, but zero is consistently included, indicating no significant influence of recycling on resource use efficiency. This result confirms that higher recycling rates do not directly lead to increases in resource productivity, which can be explained by the fact that resource efficiency is highly dependent on technological innovation, industrial process efficiency and the adoption of sustainable practices beyond simply increasing recycling rates.

In conclusion, the analysis of the impulse response functions reveals a positive and significant relationship between the recycling rate of municipal waste and the rate of circular materials use, confirming the hypothesis that measures to promote recycling contribute to the transition towards a circular economy. In contrast, the effects on environmental tax revenues, R&D expenditure and resource productivity are insignificant, suggesting that these variables are influenced by other factors. At EU Member State level, these findings underline the importance of simultaneously promoting recycling and technological innovation to ensure an effective transition to a circular and sustainable economy.

5. Conclusions

This study investigated the dynamic interdependencies between the circular economy, innovation and sustainability in the European Union over the period 2013-2023, using a VAR model to analyze the complex relationships between municipal waste recycling rates, resource productivity, circular material use rates, environmental tax revenues and gross domestic expenditure on research and development. The results underline the importance of implementing coherent, integrated and differentiated public policies at European level to support the transition to a circular economy and improve resource efficiency.

The analysis has confirmed that an increase in the recycling rate of municipal waste contributes significantly to an increase in the rate of use of circular materials, suggesting that European policies to stimulate recycling have a positive effect on the reuse of secondary materials. This result validates the effectiveness of the initiatives promoted by the Action Plan for the Circular Economy and suggests the need to extend these measures in all Member States by harmonizing standards and improving recycling infrastructures. At the same time, the results indicate that environmentally oriented fiscal policies do not have a negative impact on resource productivity, suggesting that environmental taxes implemented at European level do not negatively affect

resource efficiency. This is important for the development of a stable and innovation-friendly fiscal framework to encourage investments in sustainable technologies.

However, the results also point to some limitations of current public policies. R&D investments do not have a significant effect on resource productivity, which may suggest that the innovation strategies implemented during the period under review have not been sufficiently geared towards increasing resource efficiency. This finding highlights the need for more targeted interventions to promote the application of innovative technologies in sectors with high resource-saving potential. It was also observed that the increased use of circular materials may lead to a decrease in revenues from environmental taxes, which could pose a challenge for maintaining a sustainable budget for environmental policies.

The study also has some methodological limitations, which should be taken into account when interpreting the results. The data analyzed cover a relatively short period of time, which may influence the robustness of the conclusions in the long term. Also, the variables used in the VAR model are limited to indicators aggregated at the EU level, which may hide structural differences between Member States. In addition, the applied VAR model cannot capture non-linear effects or exogenous influences that may affect the evolution of the indicators analyzed.

Future research directions should focus on extending the period of analysis to include more recent data and on the application of advanced econometric methods to better identify causal relationships. There is also a need to deepen the analysis at Member State level to identify specific differences and to propose public policies tailored to national contexts. Investigating non-linear influences and complex interactions between variables could also contribute to a clearer understanding of how the circular economy, innovation and green taxation interact within the EU.

These conclusions underline the need for integrated public policies, combining the stimulation of the circular economy with support for innovation and adjusting fiscal frameworks to ensure a sustainable transition. It is therefore essential that the European Union continues its efforts to implement the Action Plan for the Circular Economy, complementing it with effective innovation strategies and fiscal policies adapted to the current challenges.

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