ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
25 May 2023

REVISED
27 September 2023

ACCEPTED FOR PUBLICATION
24 October 2023

PUBLISHED
2 November 2023

LETTER

Sustainability pathways in European waste management for meeting circular economy goals

Giacomo Di Foggia* and Massimo Beccarello

Department of Business and Law, University of Milano-Bicocca, Milan, Italy
* Author to whom any correspondence should be addressed.

E-mail: giacomo.difoggia@unimib.it

Keywords: waste policy, waste management, circular economy goals, environment, development

Abstract

This study explores trends in recycling rates and municipal solid waste landfilling to construct a circularity index (CI) forecasted up to 2035. This projection is contrasted with the pathways that countries must adopt to attain set targets. We further estimate the impact of the CI on factors such as sustainability performance, innovation, commodity trade balance, and waste reduction. Moreover, we provide policy implications useful for designing industrial and environmental strategies, including accelerating permit approval times for waste treatment facilities, introducing more flexibility in state aid rules, empowering service users or waste generators, implementing tax credits, and leveraging specialized funds. These strategies are aimed at supporting the recycling industry to stimulate convergence and achieve circular economy objectives.

1. Introduction

The European circular economy (CE) targets foresee 65% of municipal solid waste (MSW) recycled, and less than 10% of MSW disposed of in landfills by 2035 (Kostakis and Tsagarakis 2022).

Defining reliable metrics for evaluating CE is an open field of research (Camana *et al* 2021). This issue also provokes discussion in data-driven policy design (Nikolaou and Tsagarakis 2021). Provided there is sound governance, such policies are necessary for a smooth transition to CE (Cramer 2022).

Although there is evidence of a tendency toward waste management performance convergence (Castillo-Giménez *et al* 2019), the imbalance in MSW treatment capacity across European Member States (EMSs) is a significant barrier to achieving these targets (di Foggia and Beccarello 2022).

Given the tight deadlines it is understood that accommodating policies are necessary, such as primary and supplemental policy instruments, e.g. materials taxes, extended producer responsibility, and technical requirements to promote resource efficiency (Ekvall *et al* 2016). Another study also proposed a policy mix-based analytical strategy for understanding resource efficiency in the EU, focusing on instrument design, policy synergies, and coherence (Wilts and O'Brien 2019).

Recent expectations regarding the role of policies in boosting the CE include more rigorous production standards and norms, increased circular procurement, tax breaks for circular products, tax reform for circular products, liberalization of waste trading (Hartley *et al* 2020).

Within the context of the Green Deal's two main policy paths, energy transition and CE, a promising framework has recently emerged. This includes support measures for the energy transition, such as a plan for energy efficiency, clean energy production, and diversification of energy supplies (Beccarello and di Foggia 2023), as well as the Temporary Crisis and Transition Framework, and the Green Deal Industrial Plan (Lemonnier 2023). However, the challenge remains to adapt these to CE.

Previous literature analyzed the determinants and the CE performances of EMSs to assess their progress towards the achievement of CE objectives (Marino and Pariso 2020, Robaina *et al* 2020). In our study, we pose five research questions that investigate how well EMSs are performing and to what extent the circularity index (CI) contributes to sustainable development, innovation, resilience of raw materials sectors, and reduction of MSW generated.

To answer these questions, we first estimated the recycling and landfilling rates up to 2035 using historical trends to appraise the hypothetical path that EMSs need to follow to meet CE goals. Second, we developed a CI to contextualize the role and relationship of CE goals from a broader sustainability policy-making perspective. Finally, we built a model to measure the impact of CI on sustainability, innovation raw materials sector, and waste reduction.

It is anticipated that the mean CI increased from 39.4 in 2011 to 54.4 in 2021, indicating an overall improvement in CE performance during this timeframe. Results also suggest that CI positively impacts on sustainability performance, innovation score, and raw materials sector competitiveness. In contrast there is no evidence on waste generation reduction.

The added value of this letter to the existing body of knowledge is linked to multiple contributions. First, this letter quantifies member states' progress in achieving CE goals. Stemming from this, a CI is developed, amalgamating performances based on recycling and landfilling rates. By analyzing contemporary trends in solid waste management, explicitly recycling and landfilling, this letter forecasts the trajectory of the CI up to 2035. Additionally, it suggests pathways that nations can adopt to realize their CE targets. Central to our methodology is the aspiration to foster convergence within Europe, aiding EMSs lagging in bridging the gap.

The reminder of this letter is organized as follows: section 2 resumes some pertinent literature. Section 3 contains the research methodology, including: research questions and hypotheses, data management and variable definition, and model setup. Prominent pieces of evidence are summarized in section 4 and discussed in section 5. Conclusions follow.

2. Background literature

Globally, the discourse around waste management and its critical role in advancing the CE has gained momentum, emphasizing the importance of a well-informed approach based on measurable goals. The increasing pressure to protect the environment means that countries are being urged to adopt CE models (Ghisellini *et al* 2014, Kirchherr *et al* 2017), characterized by reduction, reuse, and recycling activities (Kirchherr *et al* 2017). In light of this ongoing change, it is consequential that the importance of waste management facilities has been elevated at the policy level (Tisserant *et al* 2017, Makarichi *et al* 2018, Zeller *et al* 2019).

There is an interest in waste management options, with CE goals calling for technologically advanced facilities (Swart and Groot 2015), provided that such facilities can be vital in an integrated waste management system (Cobo *et al* 2018). However, this may increase the cost of waste management.

Consideration must be given to the fact that the approach toward waste management and the possible technologies used depend on the local context (Yao and van Woerden 2018) as well as the benefits derived from waste management efficiency, which incorporates the environmental, social, and economic spheres (Loures 2015, Blagojević and Tufegdžić 2016). Consequently, a coherent waste management policy must also consider these three dimensions (Allesch and Brunner 2014).

Despite the implications for growth demonstrated by econometric studies, significant underinvestment persists in the area of waste management (Amann *et al* 2016). Previous studies have confirmed the importance of WtE in an integrated waste management cycle (Massarutto 2015), despite the fact that policymakers and local communities have often opposed such facilities (Bocken *et al* 2014). That said, many scholars agree that the introduction of intermediate treatments is recommended (Trulli *et al* 2018).

Therefore, the development of treatment capacity within an industrial development path for the waste management sector is necessary to pave the way for investments in more efficient waste management technologies (Malinauskaite *et al* 2017, Liu *et al* 2019).

Policymakers should strike a balance between different options to achieve CE goals, especially when the recovery of materials is maximized (Zaman 2016) in the context of the growing need to incentivize secondary raw material markets (Schreck and Wagner 2017).

The European Commission is increasingly raising awareness and responding to the environmental urgency with policies on the CE as the CE plans for a cleaner and more competitive Europe (Camilleri 2020). Expectations to increase competitiveness, promote economic growth, and create jobs while reducing environmental impacts and resource dependency are high (Calisto Friant *et al* 2021). Therefore, it is worth highlighting that such expectations are deemed to be met under business as usual if EMSs need asymmetric support.

Our results will provide policymakers with reliable benchmarking information useful to set up waste capacity industrialization policies and support EMSs in developing policies aimed at promoting the overall efficiency of the service while meeting the environmental targets set by the CE package.

3. Research methodology

3.1. Context and scope of research

The MSW management chain can be modeled by dividing it into two sequential stages that differ both technically and economically. The separation of mixed and sorted waste occurs in the collection and transportation phase, while recyclable waste is

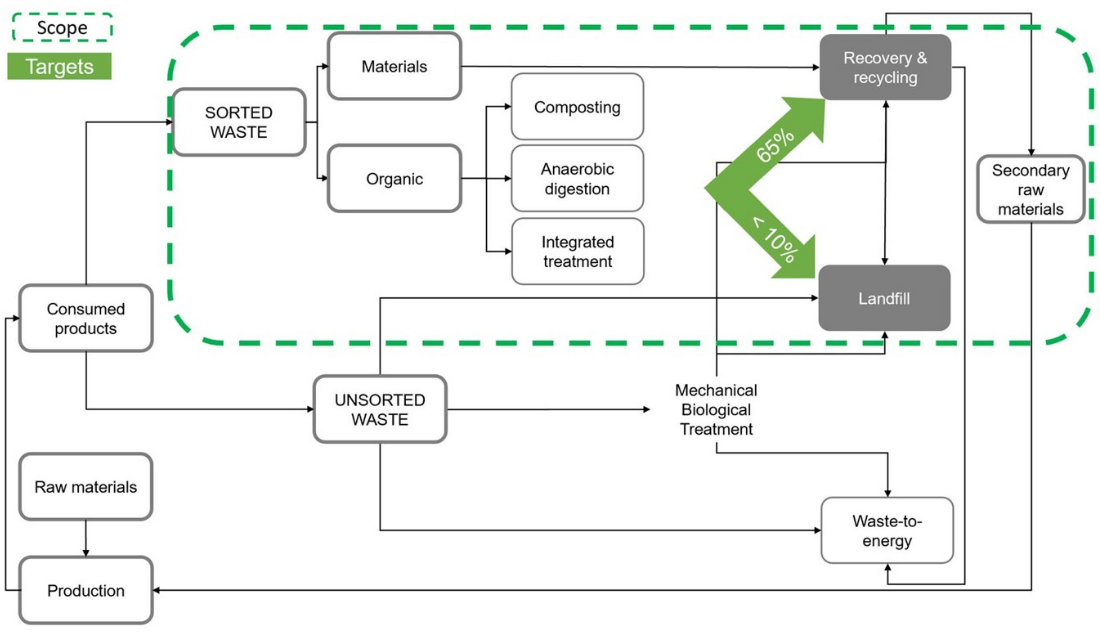

Figure 1. Research scope and CE targets within the MSW management chain.
Source: Authors' elaboration.

processed, and residual waste is disposed of in the treatment and disposal phases. Depending on treatment capacity and policy direction, disposal typically takes place through landfill or incinerator facilities, including waste to energy (WTE) plants (Zaman 2016) that rank higher in the waste hierarchy than landfilling (Gharfalkar *et al* 2015). The MSW management chain and roles of different operators vary substantially across countries (Pires *et al* 2011). Consequently, it is becoming increasingly important to lay the foundations for designing environmentally, economically, and socially efficient waste management systems (Rodrigues *et al* 2018). Figure 1 presents an overview of the MSW chain.

The European Commission adopted the European Green Deal in December 2019 to achieve climate neutrality by 2050 (Wolf *et al* 2021). The latest action plan to accelerate the transition to a CE was issued in 2020 (Johansson 2021). Such ambition is indeed high, including stricter recycling standards and binding targets for material use and the carbon footprint. Through the standards to be set, products placed on the EU market will be designed to last longer, be easier to reuse, repair, and recycle, and contain recycled materials to the greatest extent possible. The plan also focuses on sectors that use the most resources and have a high potential for circularity.

3.2. Research questions

As the CE concept emphasizes the reuse, repair, and recycling of materials and resources, the transition necessitates the establishment of advanced recycling and secondary raw materials industries to ensure the sustainable management of resources and materials. The study sets out five research questions (RQs) to investigate the relationships between CI and various sustainability outcomes, including sustainable development goal (SDG) performance, innovation score, resilient raw materials sector, and waste reduction. RQ1: how well are EMSs performing on their path to meeting European CE goals? The purpose of this wide RQ was to shed light on the probability that different EMSs have of achieving their goals by 2035. The implication is to create awareness by comparing information on EMSs' performance. RQ2: to what extent does CI contribute to sustainable development, as measured by SDG performance? RQ3: does CI positively influence the innovation score of countries? RQ4: in what ways does CI contribute to building more resilient raw materials sectors? RQ5: can CI reduce the amount of MSW generated? To investigate these research questions, the following hypotheses (Hs) were formulated. H1 predicts a struggle for convergence in EMSs performance towards meeting CE goals by 2035. H2 postulates a positive impact of CI on SDG performance. H3 suggests that CI positively affects the innovation score. H4 posits that CI fosters the resilience of raw materials sectors. Finally, H5 conjectures that CI contributes to reducing the quantity of MSW produced.

3.3. Data management and variables

In order to project the performances to 2035, three variables were defined as follows: *observed* is the 2011–2021 trend of either recycling or landfilling rates available in the EUROSTAT CE database. The variable named *predicted* is a linear prediction of such targets to 2035. Finally, *compliance* is the estimated

Table 1. Recycling and landfilling rates.

Variable	Scope	Mean	Std. dev.	Min	Max
Recycling	o	35.906	15.203	8.300	69.000
	b		14.251	12.109	66.218
	w		5.908	17.343	56.443
Landfilling	o	38.100	29.588	0.215	105.164
	b		28.821	0.874	84.179
	w		8.536	11.697	77.993

Source: Authors' elaboration. N: 297, n: 27, T: 11. Scope: o: overall, w: within, b: between.

recycling and landfilling rates that EMSs shall follow according to the CE goals compliance path as in equation (1) where x_{gi} indicates the average yearly increase required for a specific country i to meet a designated target g (either recycling or landfilling rate) by the year 2035

$$x_{gi} = \frac{x_{gi}^{t} - x_{gi}^{a}}{\text{year}^{t} - \text{year}^{a}}. \quad (1)$$

Equation (1) determinates the difference between the 2035 target x_{gi}^{t} and the actual percentage in a given year i.e. 2021 x_{gi}^{a}, and then divides this value by the difference in years between 2035 and the latest available year i.e. 2021. Table 1 summarizes the recycling and landfilling rate variables in the panel data.

Since the study empirically aims to assess the role of CE performance in the competitiveness and sustainability of the EMSs, pertinent variables were defined and operationalized to run the analyses. BAL resumes the balance of trade of raw materials between EMSs and is used as a proxy for competitiveness; data source: EUROSTAT database on raw materials. To measure the circularity of waste management systems, CI is the CE performance index, which considers the two pillars of the CE investigated in this paper: landfilling rate and recycling data source: EUROSTAT CE statistics. ENV is the ratio of environmental protection expenses and taxes, reflecting the intensity of environmental spending. GDP is the per capita gross domestic product to capture the economic context; data source: EUROSTAT environmental statistics. INN is the innovation score obtained from the European innovation scoreboard published by the European Commission; data source: European Commission Innovation score. INT stands for the interaction between CI and WtE to understand if the role of WtE remains constant or changes according to the level of CI. MSW corresponds to the total amount of MSW generated; source, while PSW captures the per capita MSW production in kg; data source: EUROSTAT waste management statistics. The study assesses the sustainable development performance of the EMSs through SDG, which is the sustainable development goal performance obtained from the UN dedicated website. WtE is also considered in this context as the share of waste treated in WtE plants. Table 2 provides additional information and key descriptive statistics of the variables used to model the data.

The data analysis consisted of two steps. The first step was a comparative assessment of the performance of the EMSs based on their performance in achieving the objectives listed in the CE package. Based on an analysis of past years and current conditions, this forecast can provide notable preliminary points to consider not only regarding CE goals but also with reference to economic development, job creation, and competitiveness. The values of the compliance variable were obtained starting from the recycling percentage of 2021 and adding to this, year by year, until 2035, following a parametric linear factor.

3.4. Model setup

The impact of circularity on prominent variables could be studied using regression analysis; linear panel models can be described through restrictions of the following general model as in equation (2) where $i = 1,\ldots,n$ is the group component whereas $t = 1,\ldots,T$ is the time; and a random disturbance μ_{it} of mean 0 taking into consideration that μ_{it} is not estimable with $N = n \times T$,

$$xy_{it} = \alpha_{it} + \beta_{it}^{T} x_{it} + u_{it}. \quad (2)$$

A great deal of assumptions are usually made about the parameters, the errors and the exogeneity of the regressors; the parameter homogeneity, which means that $\alpha_{it} = \alpha$ for all i,t and $\beta_{it} = \beta$ for all i,t is a commonly accepted assumption resulting in a linear model pooling all the data across i and t,

$$y_{it} = \alpha + \beta^{T} x_{it} + u_{it}. \quad (3)$$

To model individual heterogeneity, one often assumes that the error term has two separate components, one specific to the individual and does not change over time. This is called the unobserved effects model showed in equation (4),

$$y_{it} = \alpha + \beta^{T} x_{it} + u_{it} + \varepsilon_{it}. \quad (4)$$

The appropriate estimation method for this model depends on the properties of the two error

Table 2. Descriptive statistics.

Var.	Input	Scope	Mean	SD.	Min	Max
BAL	Exp.–Imp. of materials	o	−135.724	3407.523	−13 116	15 364.9
		b		3430.075	−9997.6	12 069.97
		w		493.232	−3603.5	3159.20
CI	$\frac{\text{Rec}+100-\text{lan}}{2}$	o	48.903	21.799	2.868	84.15
		b		21.076	13.965	82.672
		w		6.782	22.212	65.387
ENV	$\frac{\text{Env. expense}}{\text{Env. taxes}}$	o	0.786	0.29	0.298	1.787
		b		0.27	0.352	1.432
		w		0.117	0.389	1.173
GDP	$\frac{\text{GDP } m}{\text{Population } m}$	o	28.609	19.828	5.592	113.899
		b		19.76	7.225	98.48
		w		3.986	9.414	56.083
INN	—	o	95.003	31.783	32.035	149.168
		b		31.661	35.702	141.245
		w		6.451	46.209	121.562
INT	CI × WtE	o	1433.85	1530.888	0	12 398.6
		b		1367.484	2.952	3929.389
		w		732.654	−443.65	11 790.14
MSW	—	o	8.085	12.067	0.257	53.748
		b		12.167	0.296	51.244
		w		1.611	−16.335	11.404
PSW	$\frac{\text{MSW}}{\text{POP}}$	o	495.747	133.736	246.796	845.148
		b		126.775	265.574	817.06
SDG	—	o	78.38	3.499	70.97	86.48
		b		3.4	72.583	86.072
		w		1.038	75.173	80.594
WTE	$\frac{\text{Waste in WtE}}{\text{MSW}} \times 100$	o	22.406	20.943	0	187.008
		b		18.302	0.109	53.679
		w		10.72	−5.689	176.569

Source: Authors' elaboration. Note: rec: recycling rat, lan: landfilling rate. *N*: 297, *n*: 27, *T*: 11. Scope: o: overall, w: within, b: between.

components. The idiosyncratic error ε_{it} is usually assumed to be well-behaved and independent of both the regressors x_{it} and the individual error component μ_i. The individual component may be either independent of the regressors or correlated. Starting from the above consideration, the following model was set up as formalized in equation (5)

$$y_{it} = \alpha + \beta_1^T \text{CI}_{it} + \beta_1^T \text{WTE}a_{it} + \beta_1^T \text{GDP}_{it} + \beta_1^T \text{ENV}_{it} + \beta_1^T \text{MSW}_{it} + \beta_1^T \text{INT}a_{it} + u_{it} + \varepsilon_{it} \quad (5)$$

where y = SDG, PSW, INN, BAL respectively, $t = 2011, 2021$, and $i = \text{EMS}$.

4. Results

In this section, we report the results of our analysis. Figure 2 illustrates the evolution of the CI from 2011 to 2021. The mean CI increased from 39.4 in 2011 to 54.4 in 2021, indicating an overall improvement in the CE performance of EMSs during this timeframe. Additionally, there is evidence of a slight yet consistent convergence toward a more homogeneous distribution of the CI values, as reflected by the standard deviation decreasing from 23.2 in 2011 to 19.9 in 2021.

The results from the model set in equation (5) are presented in table 3. CI positively impacts sustainable development (0.081***) given that the CE aims to keep resources in use for as long as possible, thereby reducing waste and minimizing negative environmental impacts; it seems plausible that countries that adopt CE principles are likely to see positive outcomes in terms of sustainable development. This could include reduced greenhouse gas emissions, improved resource efficiency, and increased economic resilience.

In addition, CI positively affects the innovation score (0.208***), presumably because countries that embrace CE principles are likely to be more innovative because CE principles require innovative thinking and new approaches to product design, resource

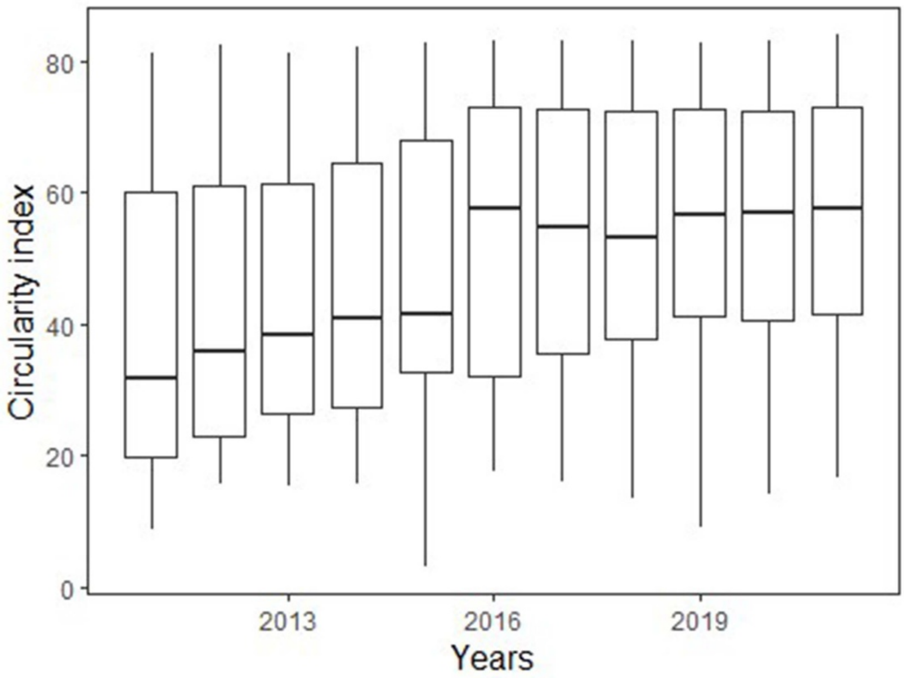

Figure 2. Evolution of CI.
Source: Authors' elaboration.

management, and waste reduction. Such countries may also benefit from new markets due to more sustainable products and services.

Also, CI contributes to creating more competitive and resilient raw materials sectors (16.57***), as the CE can improve the economy's competitiveness by creating more resilient raw materials sectors. This could include the development of new supply chains, the use of more sustainable materials, and the adoption of new business models that prioritize resource efficiency.

However, no evidence of municipal waste reduction emerged (1.325***). While there is no evidence that CI leads to reduced municipal waste production, it is worth noting that waste generation prevention is a prominent principle in the waste hierarchy and a benefit of the CE. Systems that prioritize resource efficiency and waste reduction help minimize the amount of waste which reduces negative environmental impacts. Table 3 shows the results of equation (5).

The study found a significant relationship between WtE capacity and SDG performance, indicating that countries with higher WtE capacity tend to have better sustainable development outcomes. However, the relationship between the share of MSW treated in WtE plants and innovation score was found to be non-significant regarding trade impact. The results also indicate a significant interaction effect between CI and WtE on the sustainability measure (−0.000 954**), where the positive effect of WtE capacity tends to be stronger at lower industrialization levels but diminishes at higher industrialization rates.

In contrast, in more advanced countries, the positive impact of WtE capacity is less pronounced. Similarly, the positive effect of WtE capacity on waste reduction is stronger in countries with a lower CI but weaker in countries with higher performance. Countries with higher GDP per capita generally have more resources and financial capacity to invest in sustainable development (0.0601***) and innovation (0.409***), including funding for research and development, infrastructure improvements, regulatory frameworks aimed at reducing the environmental impact of economic activities and effective environmental protection expenses (0.869). Figure 3 shows historical trend and the projected path of the CI.

Over the last decade, EMSs have significantly improved their CE performance, as evidenced by the increase in the average circularity index from 39.4 in 2011 to 54.4 in 2021. From table 3, one can underscore the importance of investing in the CE industry, revealing its positive impact on sustainable development, innovation, and the competitiveness of the raw materials sectors. However, the findings also highlight that municipal waste reduction has not yet been achieved. Investing in the CE can promote sustainable development, reduce negative environmental impacts, and drive innovation by encouraging new approaches to product design and resource management. Furthermore, the CE can bolster economic resilience by fostering more competitive and sustainable raw materials sectors.

Table 3. Regression analysis.

	SDG	INN	BAL	PSW
	Sustainable development	Innovation score	Balance of trade	Waste generation
CI	0.0811***	0.208***	16.57***	1.325***
	(0.008 76)	(0.0705)	(5.307)	(0.439)
WTE	0.0658**	0.285	−24.74	−5.573***
	(0.0306)	(0.247)	(18.43)	(1.538)
GDP	0.0601***	0.409***	10.93	2.804***
	(0.0127)	(0.0974)	(8.162)	(0.608)
ENV	0.869**	7.830**	−80.26	61.73***
	(0.421)	(3.383)	(254.0)	(21.07)
MSW	0.0408	0.134	−170.4***	3.462**
	(0.0341)	(0.227)	(29.40)	(1.426)
INT	−0.000 954**	−0.002 65	−0.128	0.0842***
	(0.000 456)	(0.003 69)	(0.271)	(0.0230)
Constant	71.57***	63.30***	920.1	278.3***
	(0.734)	(5.237)	(721.0)	(32.79)
Observations	297	297	297	297
Number of id	27	27	27	27
σ_u	2.449	14.274	3281.612	90.132
σ_e	0.807	6.362	483.251	39.546
ρ	0.9021	0.834	0.978	0.838
R2				
Between	0.457	0.114	0.144	0.346
Within	0.336	0.804	0.226	0.363
Overall	0.343	0.756	0.224	0.354

Source: Authors' elaboration. Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Given these benefits, countries must prioritize investments in the CE industry to improve their circularity index and achieve long-term environmental, economic, and social sustainability.

5. Discussion and policy implications

This article shares some similarities with previous literature. In similar works, resource productivity was selected as a proxy of the countries' economic circularity (Robaina *et al* 2020). Similarly, another study grouped the EMs according to their performance using CE indicators proposed by the EC. Interestingly, the paper underlined that only a few of the adopted development strategies might be considered effective in meeting the challenges of CE according to the EU's standards (Mazur-Wierzbicka 2021). Regarding the relationship between CE and SDGs, this paper goes in the same direction as a recent study, whose findings provide policymakers with relevant insights into the consequences of policies that promote the CE, above all on the difference in outcomes depending on prominent CE fields such as renewable energy, reuse, repair, and recycling (Knäble *et al* 2022). Findings also comply with the suggestions of a recent study analyzing the relationship between waste management policies and CE goals, which suggests that policymakers should urgently focus on such policy implications (D'Adamo *et al* 2022). Finally, it is important to underline that a shift to a CE can have remarkable sectoral distributional effects among countries and sectors. Therefore, CE policies need the support of supplementary re-distributional policies (Boonman *et al* 2023).

Our results provide policymakers with information for charting out a waste capacity industrialization path and regulators with data regarding how and to what extent they should define tariffs for the use of facilities (Scharff 2014, Schreck and Wagner 2017). Specifically, these results can support policymakers in designing policies that promote the overall efficiency of the waste management industry to meet CE goals. It is also important to focus policies on the infrastructural capacity of the waste sector by selecting and promoting different waste management structures based on the existing treatment capacity and the objectives to be achieved (di Foggia and Beccarello 2021). However, for this to happen, there must be broad political agreement, as it is a difficult path, given the complexity of obtaining permits to build new structures and the management of consensus by policymakers.

Results also show that the European command and control approach must be supplemented by additional policy measures to promote convergence among member states.

This letter has policy implications. First, authorization times for waste treatment facilities shall be

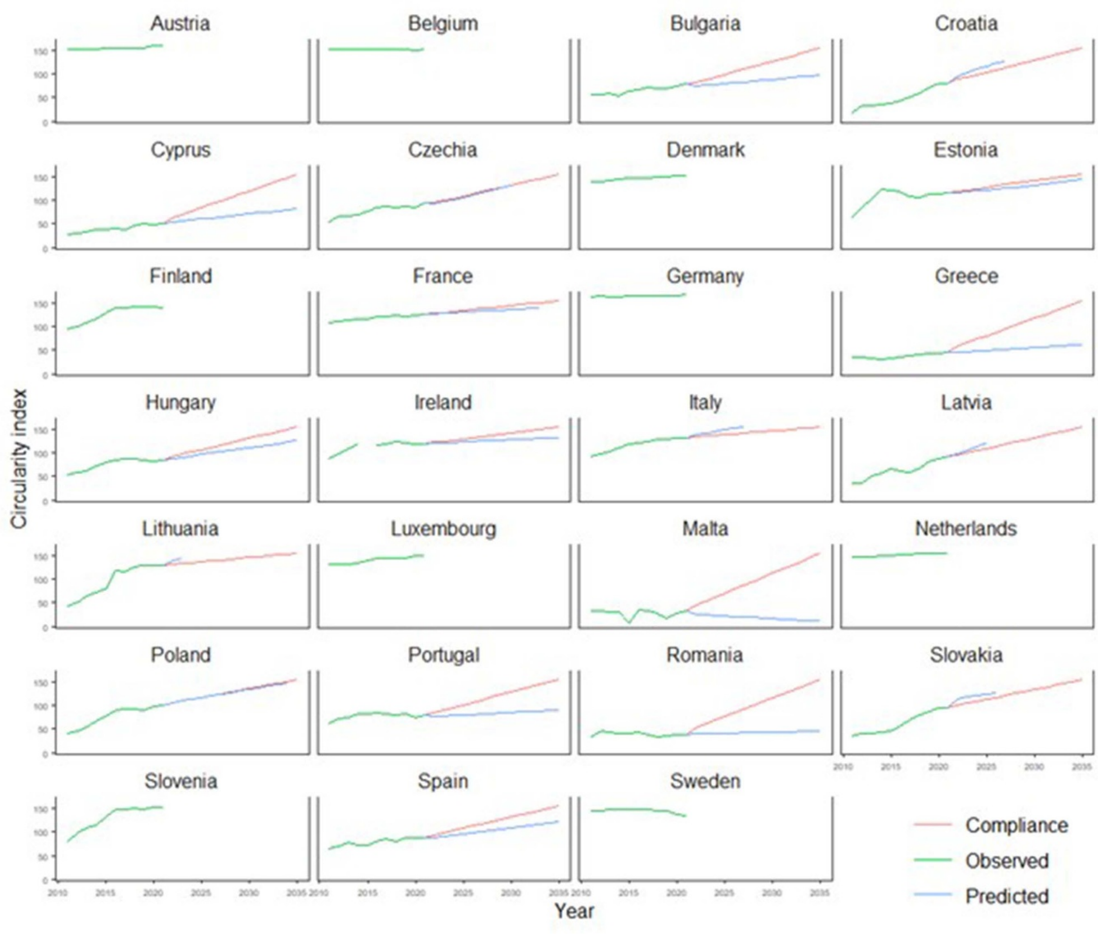

Figure 3. Projected circularity index.
Source: Authors' elaboration.

reduced along with the introduction of simplified procedures for the authorization processes in analogy to as envisaged by RePowerEU to accelerate investments in renewable production. One-stop-shop procedures should also be introduced for facilities functional to CE goals to enhance certainty to private investors.

Second, greater flexibility regarding state aid. It is necessary to strengthen the measures to support investments for the CE by extending the extraordinary measures envisaged by the European Temporary Crisis and Transition Framework to investments to achieve the recycling and landfill reduction targets. It would be appropriate: (i) to derogate from the current state aid framework by increasing aid schemes for investments in waste treatment facilities, (ii) to simplify the notification procedures by including investments in CE in a General Block Exemption with relevant threshold values below which it is not necessary to notify the investment aid.

Third, tax credit schemes to promote investments reduce or prevent waste production or improve the quantity and quality of sorted waste.

Fourth, the Just Transition Fund shall provide for the less-performing EMSs specific measures to strengthen human and professional skills, which will be increasingly important to ensure a waste collection and treatment system in line with CE goals.

Fifth, CE goals may constitute a driving force for promoting EU leadership regarding the production capacity of waste management and treatment technologies. It is, therefore, necessary that alongside the projects that promote research on key technologies for the CE, specific measures are developed to promote industrial development. While our analysis yielded significant insights, it should be acknowledged that it is not exempt from limitations as alternative approaches could be employed for prediction by adjusting the baseline, especially given that the alternative scenario aligns with common EU targets for 2035. To this end, we have introduced an alternative prediction method using an autoregressive moving average, comparing its results with the used approach. The outcomes often show slight variations, with some predictions closely aligning with the original results. Summarizing the differences between the two methods at the European level, the ratio of the average CI between the approaches stands at 1.031 in 2028, i.e. half of the predicted period, and 0.99 in 2035, supporting the viability of our proposed approach.

6. Conclusions

The need to understand how and to what extent waste management systems need to be upgraded and supported to meet the CE goals set forth in the CE package, justifies our research approach.

First, we analyzed the recycling and landfilling rate trends, merged in a CI and, by predicting them until 2035 from a business-as-usual perspective. We compared such predictions with the path countries shall hypothetically follow to meet CE goals.

Using the CI as a reference variable, we modeled the impact of the index with prominent variables such as sustainability performance, innovation, raw materials sectors competitiveness, and waste generation, to better contextualize waste management capacity in the policymaking debate.

In light of policy measures for supporting energy transition, a parallel was drawn with regard to the CE industry. Five policy implications were identified to accelerate the development of structural interventions in facilities relating to waste treatment to increase recycling capacity and reduce waste landfilling. Authorization times for waste treatment facilities shall be reduced along with the introduction of simplified authorization procedures, more flexibility on state aid rules, allowing service users or waste producers, the use of tax credit schemes, and the application of the Just Transition Fund to provide less-performing EMSs with specific measures to strengthen human and professional skills and specific measures to promote industrial development.

Our results can significantly assist policymakers in defining industrial policies that facilitate the creation of appropriate technological options, thereby supporting a country's ability to achieve CE goals. Future studies should focus on three topics. First, it is important to analyze the cost-effectiveness of different waste management technologies. Second, there is a need to understand the regulatory role of waste management tariffs in the development of facilities to ensure optimal capacity. Third, future research should focus on market structure as it is crucial in designing a single European market for waste management compliant with leadership in environmental targets.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.5281/zenodo.7655120.

ORCID iDs

Giacomo Di Foggia https://orcid.org/0000-0003-4296-1312

Massimo Beccarello https://orcid.org/0000-0002-7065-1402

References

Allesch A and Brunner P H 2014 Assessment methods for solid waste management: a literature review *Waste Manage. Res.* **32** 461–73

Amann E, Baer W, Trebat T and Lora J V 2016 Infrastructure and its role in Brazil's development process *Q. Rev. Econ. Finance* **62** 66–73

Beccarello M and di Foggia G 2023 Review and perspectives of key decarbonization drivers to 2030 *Energies* **16** 1345

Blagojević M R and Tufegdžić A 2016 The new technology era requirements and sustainable approach to industrial heritage renewal *Energy Build.* **115** 148–53

Bocken N M P, Short S W, Rana P and Evans S 2014 A literature and practice review to develop sustainable business model archetypes *J. Clean. Prod.* **65** 42–56

Boonman H, Verstraten P and van der Weijde A H 2023 Macroeconomic and environmental impacts of circular economy innovation policy *Sustain. Prod. Consum.* **35** 216–28

Calisto Friant M, Vermeulen W J V and Salomone R 2021 Analysing European Union circular economy policies: words versus actions *Sustain. Prod. Consum.* **27** 337–53

Camana D, Manzardo A, Toniolo S, Gallo F and Scipioni A 2021 Assessing environmental sustainability of local waste management policies in Italy from a circular economy perspective. An overview of existing tools *Sustain. Prod. Consum.* **27** 613–29

Camilleri M A 2020 European environment policy for the circular economy: implications for business and industry stakeholders *Sustain. Dev.* **28** 1804–12

Castillo-Giménez J, Montañés A and Picazo-Tadeo A J 2019 Performance in the treatment of municipal waste: are European Union member states so different? *Sci. Total Environ.* **687** 1305–14

Cobo S, Dominguez-Ramos A and Irabien A 2018 From linear to circular integrated waste management systems: a review of methodological approaches *Resour. Conserv. Recycl.* **135** 279–95

Cramer J 2022 Effective governance of circular economies: an international comparison *J. Clean. Prod.* **343** 130874

D'Adamo I, Mazzanti M, Morone P and Rosa P 2022 Assessing the relation between waste management policies and circular economy goals *Waste Manage.* **154** 27–35

di Foggia G and Beccarello M 2021 Market structure of urban waste treatment and disposal: empirical evidence from the Italian industry *Sustainability* **13** 7412

di Foggia G and Beccarello M 2022 An overview of packaging waste models in some European countries *Recycling* **7** 38

Ekvall T, Hirschnitz-Garbers M, Eboli F and Śniegocki A 2016 A systemic and systematic approach to the development of a policy mix for material resource efficiency *Sustainability* **8** 4

Gharfalkar M, Court R, Campbell C, Ali Z and Hillier G 2015 Analysis of waste hierarchy in the European waste directive 2008/98/EC *Waste Manage.* **39** 305–13

Ghisellini P, Cialani C and Ulgiati S 2014 A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems *J. Clean. Prod.* **114** 11–32

Hartley K, van Santen R and Kirchherr J 2020 Policies for transitioning towards a circular economy: expectations from the European Union (EU) *Resour. Conserv. Recycl.* **155** 104634

Johansson N 2021 Does the EU's action plan for a circular economy challenge the linear economy? *Environ. Sci. Technol.* **55** 15001–3

Kirchherr J, Reike D and Hekkert M 2017 Conceptualizing the circular economy: an analysis of 114 definitions *Resour. Conserv. Recycl.* **127** 221–32

Knäble D, de Quevedo Puente E, Pérez-Cornejo C and Baumgärtler T 2022 The impact of the circular economy on sustainable development: a European panel data approach *Sustain. Prod. Consum.* **34** 233–43

Kostakis I and Tsagarakis K P 2022 Social and economic determinants of materials recycling and circularity in Europe: an empirical investigation *Ann. Reg. Sci.* **68** 263–81

Lemonnier V 2023 The EU green deal industrial plan *Eur. State Aid Law Q.* **22** 2

Liu Y, Ge Y, Xia B, Cui C, Jiang X and Skitmore M 2019 Enhancing public acceptance towards waste-to-energy incineration projects: lessons learned from a case study in China *Sustain. Cities Soc.* **48** 101582

Loures L 2015 Post-industrial landscapes as drivers for urban redevelopment: public versus expert perspectives towards the benefits and barriers of the reuse of post-industrial sites in urban areas *Habitat Int.* **45** 72–81

Makarichi L, Jutidamrongphan W and Techato K 2018 The evolution of waste-to-energy incineration: a review *Renew. Sustain. Energy Rev.* **91** 812–21

Malinauskaite J *et al* 2017 Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe *Energy* **141** 2013–44

Marino A and Pariso P 2020 Comparing European countries' performances in the transition towards the Circular Economy *Sci. Total Environ.* **729** 138142

Massarutto A 2015 Economic aspects of thermal treatment of solid waste in a sustainable WM system *Waste Manage.* **37** 45–57

Mazur-Wierzbicka E 2021 Circular economy: advancement of European Union countries *Environ. Sci. Eur.* **33** 1

Nikolaou I E and Tsagarakis K P 2021 An introduction to circular economy and sustainability: some existing lessons and future directions *Sustain. Prod. Consum.* **28** 600–9

Pires A, Martinho G and Chang N-B 2011 Solid waste management in European countries: a review of systems analysis techniques *J. Environ. Manage.* **92** 1033–50

Robaina M, Villar J and Pereira E T 2020 The determinants for a circular economy in Europe *Environ. Sci. Pollut. Res.* **27** 12566–78

Rodrigues A P, Fernandes M L, Rodrigues M F F, Bortoluzzi S C, Gouvea da Costa S E and Pinheiro de Lima E 2018 Developing criteria for performance assessment in municipal solid waste management *J. Clean. Prod.* **186** 748–57

Scharff H 2014 Landfill reduction experience in The Netherlands *Waste Manage.* **34** 2218–24

Schreck M and Wagner J 2017 Incentivizing secondary raw material markets for sustainable waste management *Waste Manage.* **67** 354–9

Swart J and Groot L 2015 Waste management alternatives: (dis)economies of scale in recovery and decoupling *Resour. Conserv. Recycl.* **94** 43–55

Tisserant A, Pauliuk S, Merciai S, Schmidt J, Fry J, Wood R and Tukker A 2017 Solid waste and the circular economy: a global analysis of waste treatment and waste footprints *J. Ind. Ecol.* **21** 628–40

Trulli E, Ferronato N, Torretta V, Piscitelli M, Masi S and Mancini I 2018 Sustainable mechanical biological treatment of solid waste in urbanized areas with low recycling rates *Waste Manage.* **71** 556–64

Wilts H and O'Brien M 2019 A policy mix for resource efficiency in the EU: key instruments, challenges and research needs *Ecol. Econ.* **155** 59–69

Wolf S, Teitge J, Mielke J, Schütze F and Jaeger C 2021 The European green deal—more than climate neutrality *Intereconomics* **56** 99–107

Yao L and van Woerden F 2018 Financing and cost recovery for waste management systems *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050* ed S Kaza, L C Yao, P Bhada-Tata and F van Woerden (World Bank) pp 101–14

Zaman A U 2016 A comprehensive study of the environmental and economic benefits of resource recovery from global waste management systems *J. Clean. Prod.* **124** 41–50

Zeller V, Towa E, Degrez M and Achten W M J 2019 Urban waste flows and their potential for a circular economy model at city-region level *Waste Manage.* **83** 83–94