

The Role of Voluntary Environmental Policies Towards Achieving Circularity

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ABSTRACT

Over the last decade, waste management and prevention have become important in the transition towards a circular economy (CE). This study explores how voluntary environmental policies, adopted at a regional level, contribute to green transition from the perspective of the CE. By considering general and region-specific trends in waste management and environmental certifications, we perform a two-step analysis on a panel of 20 Italian regions between 2015 and 2019: the first step extrapolates the relative efficiency by using a Data Envelopment Analysis (DEA), while the second step extrapolates the efficiency in terms of productivity changes supported by Malmquist Productivity Analysis (MPA). The DEA results show an overall rising trend of efficiency among the Italian regions, supported by the MPA. Furthermore, they reveal that technological innovation in Italian waste management contributes to a greater efficiency in socio-economic systems which are characterized by 'environmental federalism'. From a decision-making perspective, this study suggests that measures such as the incentivization of voluntary environmental policies should be proposed to promote techno-organizations' transition to CE, in coherence with regional economic/industrial specializations and strategies, possibly based on a diversified policy mix, setting a knowledge-based framework by using budgetary measures and policy actions at the regional level.

1. Introduction

Over the last two decades, most EU countries have experienced an increase in the generation of waste, representing a serious challenge to social and environmental sustainability, as the mismanagement of waste may critically hinder sustainable development. According to EUROSTAT, in the European Union 4.8 tons of waste were generated per EU inhabitant in 2020. Interestingly, the per capita consumption of materials varies significantly across EU member states, from 2.49 tons in Italy to about 20.9 tons in Finland (Eurostat, 2022). Moreover, global waste production is predicted to rise to 3.40 billion tons per year by 2050, which is nearly 1.69 times the current rate of 2.01 billion tons (Kaza et al., 2018; The World Bank Group, 2020).

Several countries, such as Australia, Belgium, Germany, Ireland and Slovenia, recycle more than one-third of their municipal waste.

Moreover, some European countries, including Switzerland, Germany, Sweden and Belgium, have moved away from landfilling municipal waste, focusing instead on recovering valuable materials from the waste stream, in line with Circular Economy policies. These policies, such as the Environmental Action Plan of 2020 and the EU Action Plan of 2022, aim to enhance the EU's competitiveness by safeguarding businesses against resource scarcity and price fluctuations. The goal is to transform the European Union into a resource-efficient, green, competitive and low-carbon economy (European Commission, 2011; EEA, 2011). Furthermore, the Circular Economy (CE) with resource recovery is assumed as a driving force adopted by most nations to achieve green sustainability (European Commission, 2019). The CE relies on an economic system that is designed to be restorative and generative (Charonis, 2012), avoiding primary resource demand, maintaining the value of products, materials and resources in the economy for as long as

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possible, and minimizing residual waste and emissions (European Commission, 2015). The establishment of cleaner production is of major importance in CE studies (Merli et al., 2018; Cainelli et al., 2020). Such production emphasizes reducing environmental impact and waste, as well as optimizing the performance and efficiency of the processes involved. The achievement of higher performance and efficiency is enhanced by activating the nexus among decarbonization, the CE and the bioeconomy via innovation and policy integration (Zoboli, 2019; Zoboli et al., 2020; D'Amato and Korhonen, 2021). In recent decades, a strand of scholarly literature has considered the implications of waste management efficiency in terms of economic, technical and environmental performance (Rogge and De Jaeger, 2012; Song et al., 2012; Exposito and Velasco, 2018; Romano et al., 2020). The increase in resource efficiency and the greater reduction of waste throughout the lifecycle of produced goods and services are regarded by some scholars as unexplored economic opportunities to support economic growth (Ghisellini et al., 2016; Witjes and Lozano, 2016). Waste management and prevention are strategically vital in safeguarding people's health, protecting the environment and facilitating the transition towards CE objectives (Rhyner et al., 2017; Agovino et al., 2018). This aspect can be investigated by considering the level of attention paid to environmental issues by organizations (both firms and public bodies), compared to the amount of waste produced (Cainelli et al., 2015, 2020). The objective of this study is to analyze both the overall and region-specific trends in waste management, using Italy as a case study. Specifically, it aims to investigate whether voluntary environmental policies, such as the implementation of environmental certifications, contribute to facilitating a green transition in line with the principles of the CE (Dorado et al., 2022). Environmental management systems (EMSs), such as ISO14001 and Eco-Management and Audit Scheme (EMAS), have become important strategies to deal with environmental issues (Daddi et al., 2022). The relative efficiency of regional units is valued by employing a Data Envelopment Analysis (DEA) on a panel of decision-making units (DMU) that represent the 20 Italian regions (NUTS 2) between 2015 and 2019. As has been highlighted by various authors (Halkos and Petrou, 2019; Lombardi et al., 2021), DEA has been widely used for the estimation of efficiency in waste management studies, making it the most frequently applied methodology (Pérez-López et al., 2016; Sarra et al., 2017; Caponi, 2022).

It is worth embedding the efficiency criterion within a more holistic and policy-oriented knowledge-based framework, where technology is connected to intangible assets and ultimately aims to create a decoupling pattern in a sort of IPAT (Impact \equiv Population - Affluence - Technology) paradigm (York et al., 2003). Voluntary environmental policies are possibly an overlooked part of the environmental policy making toolkit (Arimura et al., 2008). Given the complementarity between strategies of techno-organizational practices and Human Resources management (Antonoli et al., 2013), role of voluntary approaches largely depends on the existence and/or creation of stocks of intangible forms of capital, namely social, institutional and human capital. In decentralized economic systems, those forms of capital are predominantly driven by the actions of regional authorities, as it is regional government or regional agencies that deal with knowledge and innovation creation and diffusion (e.g. technological transfer, regional spillovers). Knowledge endowments are an intangible stock that public and private actors should dynamically maintain and enhance both quantitatively and qualitatively (Barbieri et al., 2023).

A further innovative investigation, exploiting the panel characteristics of the data, involves Malmquist Analysis (MPA) to evaluate the efficiency of all decision-making units (DMUs) in terms of productivity growth (Färe et al., 1989, 1992). While DEA provides a framework for measuring relative efficiency at a specific point in time, MPA extends the analysis by examining productivity changes and the underlying factors driving those changes over time. It is worth noting that MPA adds the value of panel data analysis, compared to usually cross-sectional constrained firms' surveys, such as the Community Innovation Survey

(Hashi and Stojčić, 2013). By analyzing data solely at the regional level, this study is in contrast to previous waste management studies, which focused on efficiency in several situations and at various levels: at firm level (Wursthorn et al., 2011; Stucki et al., 2023), and the municipal level (Rogge and De Jaeger, 2012; Degli Antoni and Marzetti, 2019; Lombardi et al., 2021; Rosecký et al., 2021; Ventola et al., 2021; Romano et al., 2022, 2020; Caponi, 2022; Zhang et al., 2023). The transition to sustainability is in fact driven by the co-evolution of several different transitions - environmental, demographic, fiscal, financial and technological (EEA, 2019) - occurring at different geographical and impact dimensions. Countries, regions, sectors and innovation systems are the socio-economic-technological spaces in which new business models and innovations emerge, develop and are diffused throughout territories and sectors. Economic systems that decentralise competences and governance to regional entities might witness enhanced performance due to the opportunity to link environmental and innovation policies at the local level (Diaz Lopez et al., 2023),¹ by exploiting the structure of regional innovation systems (Malerba, 1993; Cooke et al., 1997; Brusco, 1982; Costantini et al., 2013).² Within this study, the regional level is assumed to be an appropriate institutional frame, as it allows us to determine the boundaries of the impacts of CE-oriented actions (Obersteg et al., 2019), and to analyze the implementation of circularity's transformations under a systemic approach (Dagilienè et al., 2021). Moreover, as emphasized by some scholars (Zeller et al., 2019), "the question about the impact of the geographical scale is not only an environmental one: it is also highly important to the techno-economic feasibility of CE initiatives" (p. 84).

Italy is an interesting case study because it encompasses extremely locally-differentiated waste systems due to structural, technical, political and socioeconomic differences across the regions (Mazzanti and Montini, 2014; Agovino et al., 2019). Therefore, this study can provide valuable knowledge of the challenges and issues related to assessing and understanding waste sector analysis in several others countries, since European as well as global data clearly show that the waste sectors of different countries are characterized by heterogeneity (Kaza et al., 2018; Cainelli et al., 2020). In the Italian context, as is the case in Germany and Spain, regions do indeed possess strong competencies around themes such as innovation, environmental sustainability, education and training, as well as health. This comes with a substantial public expenditure figure for those subjects of policy action. In addition, regionalized data are historically available, consistently aligning with the previously mentioned 'innovation systems'. Further research might be pursued at provincial and municipal levels as well, with the remaining regions being the cornerstone of policymaking for sustainability transitions (D'Amato et al., 2013; Cainelli et al., 2015).

Specifically, the present work considers the number of Italian EMAS-registered organizations (both firms and public bodies) and the number of local units with a UNI EN ISO 14001 environmental management system certification as proxies for the level of attention paid to the environment. Indeed, the EMAS is a good index to assess the level of attention paid to environmental issues, as it focuses on the reduction of emissions and waste. Moreover, it provides a representative picture of environmental conditions, pressures on the environment and the societal responses of organizations, and it serves as a base for international

¹ <https://www.resources.org/common-resources/environmental-federalism-wallace-e-oates/>

² Cooke et al. (1997), citing Malerba (1993), state that "Italian innovation occurs, with substantial variation, in subnational and often local clusters of highly interactive small and medium-sized enterprises who are effectively untouched by the NSI". The historical role of Regional public bodies as main actors of change regarding innovation realms is also discussed by Brusco (1982). Some figures may highlight the public expenditure and policy role of regions in 'federal states': Piemonte total public expenditure is around 70 billion €; Emilia Romagna R&D expenditure is 3.5 billion €.

comparisons. EMAS and UNI EN ISO 14001 certification are voluntary policies that are not required by law or regulation. These types of policies, usually created in order to provide best practices, are flexible and inexpensive, though their effectiveness may be uncertain (Attari et al., 2009). Several authors (Rennings et al., 2006; Rehfeld et al., 2007; Demirel and Kesidou, 2011) have investigated how EMAS and ISO 14001 can support environmental technological innovation. However, to the best of the authors' knowledge, very few studies (Johansson and Corvellec, 2018), have explored how voluntary regulations/environmental policy decisions made at the regional level stimulate greater efficiency in waste recycling, and thereby contribute to organizations' (both firms and public bodies) green transition to CE.

The potential benefits associated with EMS adoption make it a fundamental tool within the environmental toolbox that a policy maker should use in an integrated manner to combine environmental protection and a more sustainable consumption and production. The choice of the European Commission to design a policy instrument based on the concept of the Deming cycle (i.e. EMAS) is undoubtable proof of the relevance that EMS standards have in the European environmental policy. Moreover, Member States and local authorities are supporting EMAS and ISO 14001 adoption through several regulatory relief and incentive measures such as extension of environmental permit duration, inspection reduction, fiscal benefit (among others Wätzold et al., 2001; Testa et al., 2014).

The paper is organized as follows. Section 2 introduces the literature review, which discusses waste and the CE. Section 3 presents the theoretical approach and methods, and describes the case selection, data gathering, and data analysis procedures used. In Section 4, the findings are outlined, while Section 5 discusses them. In the concluding section, the implications, the limitations of the study and potential future research avenues are proposed.

2. Literature Review

2.1. CE and Waste Management

In the quest to achieve sustainable development, the concept of the CE has become central, and is increasingly assumed as a complete or partial solution to environmental challenges (D'Amato and Korhonen, 2021). According to Kirchherr et al. (2017), there is the need to shift from linear to circular business models to implement sustainability and a circular economy, as the economy would be grounded on the 3R principles: the reduction, reuse and recycling of materials (Sakai et al., 2011; Preston, 2012; Korhonen et al., 2018; Figge et al., 2023), where waste becomes a resource (Skawinska and Zalewski, 2018; Sanguino et al., 2020; Belmonte-Ureña et al., 2021). Consequently, the main research stream on the CE has specifically focused on methods to better conserve value in material flows. Taking into account the centrality of the 3R principles within the CE frame, the role of manufacturing and waste management activities can be regarded as a crucial pillar for broader waste prevention strategies, which is the ultimate goal of CE actions. Innovative waste management is a core part of a robust and stable transition to circularity (George et al., 2015; Zotti and Bigano, 2019; Bauwens et al., 2020). The increase in resource efficiency and the greater reduction of waste throughout the lifecycle of produced goods and services are regarded by some scholars (Ghisellini et al., 2016; Witjes and Lozano, 2016) as unexplored economic opportunities to support economic growth. Different economic and societal stakeholders have to work together to guarantee the circular flow of materials and the benefits derived from their efficient use in order to make CE initiatives successful (Preston, 2012; Ellen MacArthur Foundation, 2015). Furthermore, legislative and financial subsidies and support can facilitate the implementation of CE initiatives and projects (Ziegler and Nogueira, 2009).

The extant literature on CE largely focuses on China and Europe and employs tools and methods for modelling processes and to support

decision-making in the implementation of CE. Several concepts are of central importance in the study of CE (Murray et al., 2017; Korhonen et al., 2018); however, waste management is the most significant sub-sector (Merli et al., 2018). According to these authors, the most explored practices are those related to cleaner production in order, on the one hand, to reduce the environmental impact and waste production of products and, on the other hand, to optimize the performance and efficiency of the processes involved.

Against this background, it is worth noting the nomenclature of CE proposed by Prieto-Sandoval et al. (2016). CE is defined as “an economic system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and materials loops, and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated in symbiosis) and macro (city, regions and governments) levels” (p. 613). In this model, firms play a significant role because they are the most numerous entities active in the market. As has been emphasized (Ormazabal et al., 2018; Ren and Albrecht, 2023), the implementation of the CE is not isolated from the general practices of environmental management, because all these practices represent the first step to achieving and correctly implementing CE. Recently, the role of businesses in the development of the CE has been emphasized, and firms' interest in CE has increased (Linder and Williander, 2017). In the extant literature, some studies consider firms and the adoption of CE, and investigate ways to help firms to implement CE at the micro level (Aminoff et al., 2016; Pauliuk, 2018). These studies largely focus on the barriers and challenges faced by firms in relation to CE implementation (Linder and Williander, 2017; De Jesus and Mendonça, 2018; Garrido-Prada et al., 2021). Other scholars have considered the best practices and enablers of CE implementation (Bocken et al., 2017; Jones and Comfort, 2017), while other authors stress the need for developing methods to assess the environmental, social and economic sustainability performance of circular products and business models (Pauliuk, 2018; Ferasso et al., 2020; Fehrer and Wieland, 2021), as well as circularity indicators at the micro level (Linder et al., 2017). Whilst younger firms may have a more environmental management mindset and are able to implement innovative practices that lead to the CE, older and medium-age firms, established and developed within the linear economy paradigm, may encounter serious challenges and barriers when adopting an approach that is clearly oriented towards sustainability. This can be explained by different reasons: consumers' perceptions, as they may experience difficulty in distinguishing between virtuous and non-virtuous firms, the lack of specific financial and policy support to facilitate ecological transition, the lack of incentives to develop in that direction and finally the limited size of the businesses, which may negatively impact or slow down any sustainable action in such firms' management (Alvarez-Garcia et al., 2018; Murmura et al., 2018). Such kinds of barriers can significantly impede economic gains/performance from the circular economy for small and medium-sized enterprises in the short term, while benefits may accrue in the medium/long term. The introduction of single practices (vis a vis a proper circular business model composed of bundles of innovations) may not be sufficient either for strong environmental effects or for improving firms' economic performance. It is hard to manage the adoption of multiple (rather than a single) and heterogeneous typologies of CE technologies, as the implementation of a fully-fledged circular business model requires dedicated competences and capabilities, such as ‘sustainability-oriented capabilities’ (Demirel and Kesidou, 2011).

Organizations have to rethink their value-creation process to devise new business models that incorporate all the principles of the CE. They should understand that the adoption of CE business models may represent a competitive advantage, as these sustainable practices may actually improve their business performance, reduce their material costs, foster information-sharing and engender cooperation to develop industrial symbiosis, which may facilitate a closed loop of materials, making their operations more profitable (Longo et al., 2005; Aragón-Correa

et al., 2020), and helping them to develop new markets (Hillary and Burr, 2011).

In the Italian context, despite the higher costs that constitute the main barrier to early-stage CE businesses, the implementation of CE practices is regarded by firms as a business opportunity, rather than a cost (Mura et al., 2020; Luthra et al., 2022). By analyzing Italian firms in the office supply sector, Ünal et al. (2019) observe that three dimensions (namely, value network, customer value proposition, and interface and managerial commitment) are interdependent, and they reinforce each other in managerial practices aimed at designing circular economy business models. Furthermore, these scholars emphasize that managerial commitment, as a moderating factor between the value network, the customer value proposition and interface dimensions, is fundamental to addressing the goals of CE business models.

If firms constitute significant players in the market on a quantitative basis, then firms' adoption of CE principles is increasingly desirable. However, we should also mention the public sector, which is one of the main contributors and facilitators of the transition towards the CE. The significance of this sector is twofold: a public administration acts as a policy maker, but it is also a major economic actor as it purchases, consumes and uses goods and services. Despite this significance, the "circularization" of the public sector itself has received only limited attention in CE research (Klein et al., 2020). Indeed, in the EU, general government expenditure represented 46.7% of GDP in 2018, and countries in the OECD spend about 15%–20% of their GDP on Public Procurement (Schwab, 2019).

2.2. Voluntary Policies for Environmental Performance

Over the last decade, the number of voluntary environmental programs and schemes that supplement mandatory requirements has increased considerably (Delmas and Terlaak, 2001; Delmas, 2002; Jiang and Bansal, 2003; Testa et al., 2018; York et al., 2018). The interest in the significance of these programs and schemes has progressively grown, as they offer "potentially important solutions for making the planet more sustainable." (King et al., 2012, 104).

The European Eco-Management and Audit Scheme (EMAS) and the international standard ISO 14001 are the two main EMS (Eco-Management System) international standards. The EMAS Regulation (EU 1836/93)³ was introduced in July 1993 as an environmental policy tool devised by the European Commission to support the Community's goal of sustainable development. The EMAS is a voluntary environmental management tool for firms and other organizations to achieve their environmental goals by reducing their environmental impact, and to increase their operating efficiency. In addition to the main content of the regulation of the implementation of an EMS, the EMAS regulation focuses primarily on measurable improvements in operational environmental protection and environmental performance. The main purpose of EMAS is to promote improvements in the environmental efficiency of industrial activities, allowing a company to set its own objectives and to communicate to the public the commitment it has made to the environment. ISO 14001 is the specific standard for an EMS in the ISO 14000 series, which was introduced in 1996 and revised in 2004 by the International Organization for Standardization. The main objective of ISO 14001 is to improve the environmental and regulatory performance of firms. These standards can be used to achieve firms' internal and external objectives (Murmura et al., 2018, 2021) to demonstrate the

firm's environmental responsibility and, thereby, its legitimacy. ISO 14001 as an EMAS is not a mandatory certification but is the result of the voluntary choice of the organization to establish, implement and improve its own environmental management system. In a nutshell, these standards define the general requirements for how a management system should be set up and implemented, to identify and manage the most critical environmental interactions between an organization and the natural environment, in line with a circular decision scheme called the Deming Cycle (Darnall et al., 2008; Boiral and Henri, 2012; Testa et al., 2014). The complementarity of these two standards has been enhanced by the European Commission. In 2017, the revisions of the new ISO 14001:2015 standard were integrated into Annexes I to III of the EMAS Regulation. The inclusion of the ISO 14001 requirements in the EMAS makes it easy for ISO 14001-certified entities to upgrade their environmental management system to EMAS. This means that ISO 14001-certified or EMAS-registered organizations have to comply with the same requirements, apart from specific additional requests by the European Commission concerning employees' involvement in the public disclosure of environmental performance, as required by the EMAS (Testa et al., 2014). While EMAS is a public standard provided by the European Commission (EC), ISO 14001 is a private standard.

In the extensive literature, there is no consensus on the need to adopt these standards by firms and organizations. If, on the one hand, these standards can increase firms' social legitimacy (Boiral et al., 2018; Arocena et al., 2023), on the other hand, the vagueness of the requirements and various issues in the external auditing process (Christmann and Taylor, 2006; Aragón-Correa and Rubio-López, 2007; Boiral and Henri, 2012; Ma et al., 2021; Johnstone, 2022) can reduce the effectiveness of these standards in terms of improvement in environmental performance. The effectiveness of ISO 14001 and EMAS is still under-debated and far from being supported by unequivocal results (Testa et al., 2014; Boiral et al., 2018; Heras-Saizarbitoria et al., 2020; Camilleri, 2022; Marrucci and Daddi, 2022).

Several studies (Erauskin-Tolosa et al., 2020; Johnstone and Hallberg, 2020; Mosgaard et al., 2022; Mungai et al., 2020; Comoglio et al., 2022; Flagstad et al., 2022) have analyzed the determinants of ISO 14001 adoption and its effectiveness as regards environmental performance. In terms of the effects of ISO 14001 on a firm's environmental performance, Potoski and Prakash (2005) found that this standard positively contributed to reducing the environmental impacts of U.S. firms. Analyzing firms' environmental performance in Germany, Ziegler and Rennings (2004) found that, while EMAS had no significant influence, ISO 14001 had a weak, positive effect on abatement behaviour and environmental innovations. Focusing on the relationship between ISO 14001 and expenditure on eco-innovations, some authors (Demirel and Kesidou, 2011; Inoue et al., 2013) found that the adoption of ISO 14001 has a positive impact on expenditure in environmental improvements.

3. The Analysis

3.1. Theoretical Approach and Methods

One of the key components of CE is the reduction of waste generation by reusing, repairing, refurbishing and recycling materials and products as much as possible (Merli et al., 2018). Waste is considered as a negative externality in CE (Ellen Macarthur Foundation, 2015), and minimizing waste is one of its primary objectives. Firms are responsible for producing goods and services; in this process, they generate waste. The way firms manage this waste by reusing, repairing, refurbishing and recycling materials and products, is a vital aspect of CE (Singh and Ordoñez, 2016). Regions, on the other hand, are geographic areas that encompass multiple organizations (both firms and public bodies) and other stakeholders. The way regions manage waste, by implementing policies and regulations to promote CE, can have a significant impact on the performance of firms operating in those regions. Regions also have a responsibility to manage waste generated within their boundaries, and

³ In 2001, a revised Regulation (EC) No 761/2001 (EMAS II) was adopted. Its main elements were the extension of the scope of EMAS to all sectors of economic activity including local authorities, and the integration of the international environmental management system standard EN ISO 14001. In 2009, the EMAS Regulation was revised and modified for the second time. Regulation (EC) No 1221/2009 ("EMAS Regulation") was published on 22 December 2009. The revised EMAS Regulation came into effect on 11 January 2010.

as such they have to set up policies and infrastructures to collect, sort and treat the waste. This can have an impact on the behaviour of organizations operating in the region, thus affecting their performance in terms of waste management. The performance of this way of production can be explored by considering the attention paid to environmental issues by organizations and comparing this to the volume of waste produced.

The analytical framework comprises two key methodologies to comprehensively assess regional technological innovation. Firstly, we employ an extended version of Data Envelopment Analysis (DEA), specifically DEA-Bootstrap, to gauge the intertemporal efficiency of the regions in implementing voluntary environmental policies (Bresciani et al., 2021; Puertas and Marti, 2021). This approach enables a robust evaluation by considering potential fluctuations and uncertainties inherent in the data. Additionally, to introduce a dynamic perspective and ensure the consistency of results over time, we apply the Malmquist Analysis of Productivity Growth (MPA). The MPA serves as a valuable tool for capturing changes in productivity and technological efficiency by comparing performance across different periods. Integrating the MPA into our analysis enhances its temporal dimension, allowing for a more nuanced understanding of the evolving landscape of regional green transition within the CE perspective over time. The DEA and MPA analyses provide scores that facilitate the evaluation of the performance of Decision-Making Units (DMUs) that are Italian regions. The scores are helpful in checking the efficacy of circular improvement strategies within the regional context.

3.1.1. DEA

DEA is the most frequently applied methodology and has been extensively used for efficiency estimation in waste management studies (Rogge and De Jaeger, 2012; Pérez-López et al., 2016; Sarra et al., 2017; Halkos and Petrou, 2019; Li et al., 2019; Lombardi et al., 2021; Caponi, 2022). In traditional, non-parametric frontier DEA models, as proposed by Charnes et al. (1978) and Banker et al. (1984), performance indicators are classified as inputs and desirable outputs. Inputs are the resources used to produce outputs, while outputs are products or value-added services. However, as noted in the seminal work of Koopmans (1951), the production process may also generate undesirable outputs, such as pollutants or waste. There are two main approaches for handling undesirable outputs in DEA models: direct and indirect (Scheel, 2001). Indirect approaches transform data associated with undesirable outputs into inputs or desirable outputs. However, transformations to handle undesirable outputs can lead to adverse results. On the other hand, treating the undesirable outputs in their original forms is consistent with physical laws and standard axioms of production theory (Färe and Grosskopf, 2003, 2004, 2009; Sahoo et al., 2011). Direct approaches integrate undesirable outputs into the DEA model with constraints, preserving their original form (Wang et al., 2012).

This study employs the direct approach of incorporating undesirable outputs into the DEA model with constraints, in order to investigate circular improvement strategies in terms of efficiency and productivity tools. Sarra et al. (2017), in their analysis of solid waste management, employ the annual municipal expenditure on waste services as input, and the separate collected waste and tons of unsorted waste as outputs. As the present study aims to explore the extent to which the choices made at the regional level contribute to a green transition from the perspective of the CE, it uses proxies of the level of attention to the environment as inputs.

A DEA model produces an efficiency frontier that represents the maximum level of efficiency that can be achieved by a group of DMUs (i.e. firms and public bodies). It shows the best possible performance, given a set of inputs and outputs. The efficiency score of a DMU is a measure of how close it is to the efficiency frontier. A DMU located on the efficiency frontier has an efficiency score of 1 (or 100%), indicating that it is achieving optimum performance. DMUs that are below the efficiency frontier have an efficiency score of <1 , indicating that they

have room for improvement. DMUs located on the efficiency frontier are the most efficient in their groups and serve as benchmarks or exemplars for other DMUs. These benchmarks can be used to identify best practices and areas for improvement for other DMUs.

DEA utilizes two primary models - constant returns to scale (CRS) and variable returns to scale (VRS) - that enable the identification of two distinct efficiency frontiers. CRS means that, as the level of inputs is proportionally increased, the outputs increase by the same degree, indicating a balanced and efficient use of resources without experiencing diminishing or increasing returns. In contrast, VRS implies that, as the level of inputs is proportionally increased, the outputs do not increase by the same proportion. It allows for the possibility of either increasing or diminishing returns as inputs are scaled. This suggests a more flexible production function that can adapt to changes in input levels, potentially leading to variable efficiency gains or losses depending on the scale of operation. The ratio between the CRS and VRS scores provides the scale that underlines efficiencies or inefficiencies due to scale effects.

The present research assumes that regions are not operating at an optimal scale, because the economic environment is affected by imperfect competition and numerous governmental (municipal, provincial and regional) regulations, some of which have been introduced voluntarily. Thus, the DEA model assumes VRS. Indeed, in the public sector, the decision-maker may want to maximize output and choose an output orientation. Alternatively, if the decision maker's task is to produce a given level of output with the minimum input, they will opt for an input orientation. Additionally, the output orientation is chosen. It yields technical efficiency (TE) scores, in which both outputs and inputs are measured in physical terms. Following Charnes et al. (1978) and Banker et al. (1984), the efficiency score of each DMU is determined through the solution of the following linear programming model:

$$\text{Min } \theta_0 = \sum_{i=1}^m \lambda_j x_{ij} + w_0 \quad (1)$$

$$\text{subject to } \sum_{r=1}^s \lambda_j y_{r0} = 1 \quad (2)$$

$$\sum_{r=1}^s \lambda_j y_{rj} + \sum_{i=1}^m \lambda_j x_{ij} + w_0, j = 1, \dots, n \quad (3)$$

$$\lambda_j \geq 0, \forall j, \quad r = 1, \dots, s, i = 1, \dots, m \quad (4)$$

Where θ is the efficiency of DMU j , x_{ij} is the i -th input of DMU j , y_{rj} is the r -th output of DMU j , λ_j are the weights of DMU j and w_0 the return to scale. In DEA, efficient DMUs are distinguished by achieving perfect efficiency scores of 1, while deviations from unity in both downward (input-oriented) and upward (output-oriented) directions signify varying degrees of inefficiency. In the comparison between the intertemporal analysis and cross-sectional DEA simulation, the former is considered more suitable due to its reliance on assumptions of stability and comparability between regions over the analyzed years, as opposed to the latter, which assumes yearly technical change (Bresciani et al., 2021; Puertas and Marti, 2021). In pursuit of this objective, the application of bootstrapping to DEA scores yields corrected bias and stochastic estimates, effectively minimizing the impact of statistical noise on data contamination (Simar and Wilson, 2000). The DEA-Bootstrap method is instrumental in generating a numerical simulation of DMUs within the original sample. This enables the calculation of efficiency scores across numerous simulated samples, thereby reducing data contamination.

3.1.2. MPA

Efficiency change measurement is crucial for assessing productivity growth. In the DEA approach, the MPA (Färe et al., 1992, 1989) evaluates the productivity change of DMUs over a specified period. An alternative approach involves employing DEA with sequential frontiers, commonly known as sequential MPA, as elucidated by Shestalova, 2003. This methodology, extensively detailed by Tulkens and Eeckaut (1995), offers a nuanced examination of productivity changes over time.

By leveraging DEA efficiency scores, sequential MPA yields a comprehensive set of indicators that delve into the dynamics of productivity shifts. These indicators go beyond mere overall changes, and instead break down the variations into specific components, including shifts in both efficiency and technology. This nuanced breakdown enhances the analytical capability, allowing for a more nuanced understanding of the factors driving productivity changes over the specified period.

In this analysis, the primary metrics of interest are the changes in technical efficiency (TECH) and technological change (TECCH). TECH measures the change in technical efficiency over time. It represents a shift in the efficiency frontier, indicating whether a DMU (e.g. a firm, a region) is becoming more or less efficient in utilizing its inputs to produce outputs. A TECH score >1 indicates an improvement in technical efficiency, while a score of <1 suggests a decrease in efficiency. Formally:

$$TECH(s, t) = \frac{\delta_{tw,t}}{\delta_{sw,s}} \tag{5}$$

$$TECCH(s, t) = \left[\frac{\delta_{sw,t} \delta_{sw,s}}{\delta_{tw,t} \delta_{tw,s}} \right]^{1/2} \tag{6}$$

where δ represents the distance between the period s and period t . TECCH captures the technological change component of productivity change. It reflects the advance or regression in technology and innovation over time. A TECCH score >1 indicates technological progress, implying that the DMU is adopting more advanced technologies or improving existing ones. A score of <1 suggests a decline in technology, or a failure to keep up with technological advancements.

The product between TECH and TECCH deliver the total factor productivity (TFPCH). TFPCH represents the overall change in total factor productivity, considering both technological change and changes in technical and scale efficiency. It provides a comprehensive measure of productivity change by capturing improvements or deteriorations in technology adoption and efficiency. A TFPCH score >1 indicates an increase in total factor productivity, while a score of <1 suggests a decrease.

The scale efficiency change (SECH) is another part of the overall technical efficiency provided by the VRS model. It measures the overall productivity change between two time periods by considering the change in both technical efficiency and technological progress. It provides a comprehensive assessment of how efficiently resources are utilized and the level of technological advancements achieved. The SECH index refers to the impact of the size or scale of operations on the efficiency of DMUs, and helps us to understand how the size of operations influences the efficiency of DMUs. Furthermore, it provides insights into opportunities for optimization and improvements in resource allocation. The scale effect examines how changes in the scale of inputs and outputs affect the overall efficiency of a DMU, and it can be categorized into two types: increasing returns to scale (IRS) and decreasing returns to scale (DRS). A value >1 indicates an improvement in productivity, while a value of <1 indicates a decrease in productivity. Furthermore, the MATC quantifies the extent of technological change between periods s and t by calculating the ratio of scores associated with the respective timeframes.

3.2. Data and Variables

The data used in this study have been collected from the Italian Institute of Statistics (ISTAT), which provides an annual set of statistical measures that monitor the sustainable development goals outlined in the 2030 Agenda.⁴ Inputs and outputs are extrapolated from the measures

⁴ <https://www.istat.it/it/benessere-e-sostenibilit%C3%A0/obiettivi-di-sviluppo-sostenibile/gli-indicatori-istat>

that refer to Goal 12 “Responsible consumption and production”, which is about ensuring sustainable consumption and production patterns. The database provides an indicator called “National recycling rate”, expressed in tons of material recycled, which describes the status of the CE at a national level. As Fig. 1 shows, the trend has increased over the last ten years. Unfortunately, this indicator is available only at a national level, so other indicators have been employed to analyze the CE of the Italian regions.

In this respect, the inputs employed in the analysis are: 1) the number of EMAS-registered organizations (EMAS) and 2) the number of local units (SMEs) with UNI EN ISO 14001 environmental management system certification (environ_certif) (Table 1). The outputs are desirable and undesirable: 1) the amount of separately collected municipal waste in tons (sep_waste) and 2) special hazardous waste sent for recovery operations (rec_haz_waste) are desirable outputs, while 3) the amount of municipal waste collected in tons (mun_waste) is undesirable or “bad output”. Indeed, this output should be reduced to enhance the performance of the system (Sarra et al., 2017). The decision-maker may want to increase the level of recycling, augmenting the number of organizations paying attention to environmental issues. This is crucial to boosting the desirable output as described above. The desirability of the outputs has to be understood in terms of making a positive contribution to the waste management system.

4. Results

4.1. DEA

This section presents the results of the DEA simulation for the 20 Italian regions. Efficiency scores of regions (DMU) j are computed using DEA- Bootstrap models with an output orientation, assuming that the objective of DMUs is to maximize the output. The models incorporate bootstrap replications in line with the recommendations by Simar and Wilson (2000), along with the utilization of Shepard's distances and the reciprocal value (1/value). The obtained efficiency scores are less than or equal to unity. Efficiency scores equal to unity signify a region's position on the frontier, indicating efficiency in transforming inputs to desired outputs. Conversely, a value lower than unity denotes an inefficient region, and the distance to unity reflects the percentage by which all outputs would need to be increased to achieve efficiency. The measures of efficiency, reported in the following tables of results, were obtained using STATA software.

Table 2 shows the mean, the standard deviation, and the number of times that the DMU (i.e. region) in question was efficient under both CRS and VRS from 2015 to 2019. The period witnessed moderate growth and stability for the Italian economy, and it followed the launch of the European CE strategy in December 2015, which subsequently drove the implementation of regional strategies (for example, the Emilia Romagna region launched its CE strategy at the end of 2015). Three regions (i.e. Calabria, Valle d'Aosta and Sardinia) out of twenty operated at an optimal level for almost all the period especially under CRS, as compared to the rest of the country. The overall trend is rising, which probably indicates greater attention being paid to the sustainable use of resources across regions.

Fig. 2 reports the scale effect only for the final year under analysis, 2019. It seems that, comparatively, almost all regions performed well in terms of scale, ranging from 0.54 to 1. A region located in the central Italy has the lowest scale score (i.e. Tuscany, 0.54), followed by two northern regions (i.e. Liguria, 0.55 and Lombardy, 0.56). Thirteen out of the twenty regions operate under DRS, while four regions (Abruzzo, Basilicata, Molise and Trentino Alto Adige) operate under IRS. The remaining three regions (Calabria, Aosta Valley and Sardinia) operate at CRS, which implies that these regions are currently utilizing their resources in a way that confirms their ability to operate optimally at the current scale of production, and are achieving an optimal balance in their resource utilization.

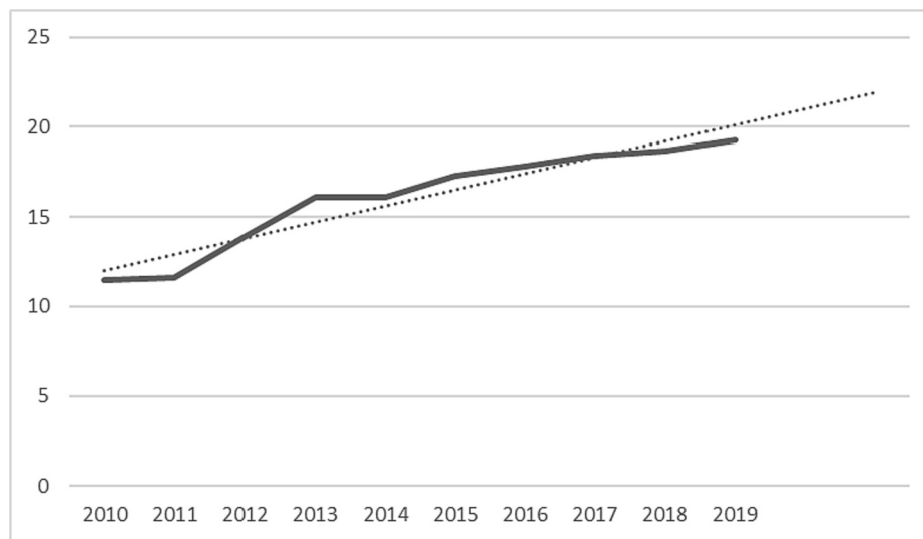


Fig. 1. Italian recycling rate: tons of solid material recycled (2010–2019). Source: elaboration on ISTAT data.

Table 1
Descriptive statistics of inputs and outputs.

Variable	Obs	Mean	Std. Dev.	Min	Max
Inputs					
EMAS	100	49.58	53.5511	1	220
environ_certif	100	916.48	803.5319	94	3773
Outputs					
sep_waste	100	822,052.8	784,099.6	31,335	3,488,628
mun_waste	100	487.58	72.13906	345	664
rec_haz_waste	100	187,353.6	285,484.5	151	1,491,364

Table A.1 in the Appendix reports the scale effects for all the periods under consideration, and the return to scales (RTS) for each region that is decreasing overall. Conventionally, this occurs when an increase in all inputs leads to a less than proportional increase in outputs. In the present analysis, this outcome might indicate that organizations' awareness is increasing, leading to a diminishing production of waste.

Table 2
Efficiency scores of the intertemporal DEA-Bootstrap (2015–2019).

DMU	CRS_TE mean	CRS_TE Std. Dev.	N CRS_TE = 1	VRS_TE Mean	VRS_TE Std. Dev.	N VRS_TE = 1
Abruzzo	0.46	0.03	0	0.74	0.01	0
Basilicata	0.45	0.04	0	0.61	0.02	0
Calabria	0.85	0.21	2	0.90	0.13	2
Campania	0.79	0.05	3	0.98	0.02	0
Emilia-Romagna	0.64	0.01	3	0.99	0.01	0
Friuli-Venezia Giulia	0.51	0.02	0	0.82	0.03	0
Lazio	0.59	0.03	0	0.94	0.02	0
Liguria	0.49	0.03	0	0.94	0.02	0
Lombardy	0.57	0.03	4	0.98	0.04	0
Marche	0.58	0.02	0	0.90	0.02	0
Molise	0.63	0.07	1	0.72	0.16	0
Piedmont	0.51	0.04	0	0.84	0.06	0
Puglia	0.59	0.08	0	0.86	0.06	0
Sardinia	0.96	0.06	2	0.97	0.03	2
Sicily	0.55	0.22	1	0.89	0.10	0
Tuscany	0.52	0.03	0	0.94	0.01	0
Trentino-Alto	0.52	0.01	0	0.80	0.02	0
Umbria	0.55	0.02	0	0.88	0.01	0
Aosta Valley	0.99	0.01	3	0.99	0.01	1
Veneto	0.60	0.03	3	0.98	0.05	1
Overall	0.62	0.17	22	0.89	0.11	6

4.2. MPA

Tables 3 and 4 provide a comprehensive summary of the results obtained through the application of the sequential MPA, respectively.

Among the measures, TECH accounts for the change in the output produced from variable inputs due to changes in the number of EMAS organizations and the number of units with environmental management system certification. TECH is also called 'catch-up', and captures the change in technical efficiency over time. On average, the majority of regions exhibited efficiency across all indicators throughout the period from 2015 to 2019 (see Table A2 in the Appendix). Certainly, almost all regions showed a TECH higher than 0.90, with the exception of Basilicata (0.89). Hence, this region needs to improve its average environmental action by increasing organizations' certifications by 11%. TECCH shows a decrease in output waste over constant input certifications. This component, also known as 'frontier-shift', captures the change in technology over time (i.e. the movement of efficiency frontiers over time). It reports efficient values, even though they do not increase over time for all regions, indicating a positive technological innovation in the sector.

The total factor productivity change (TFPCH) indicates the total output growth relative to the rise in inputs. It shows the efficiency and

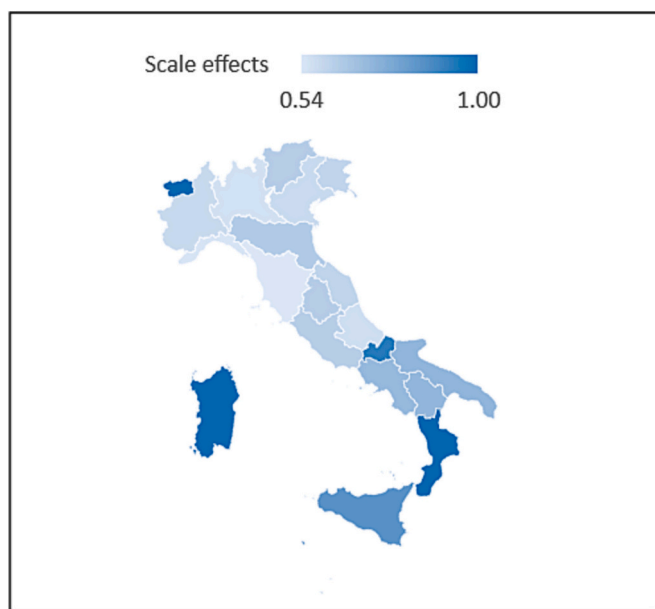


Fig. 2. Scale effects for the year 2019. Source: our elaboration.

Table 3
Annual mean efficiency changes (2015–2019) – Sequential MPA.

Years	TECH	TECCH	TFPCH	SECH	MATC
2015–2016	0.99	1.19	1.12	0.96	1.17
2016–2017	1.02	1.16	1.12	0.95	1.08
2017–2018	0.98	1.10	1.03	0.95	1.08
2018–2019	0.99	1.05	1.02	0.97	1.03
Overall	1.00	1.13	1.07	0.96	1.09

Table 4
Mean efficiency changes by DMU (2015–2019) – Sequential MPA.

DMU	TECH	TECCH	TFPCH	SECH	MATC
Abruzzo	0.99	1.07	0.98	0.93	1.07
Basilicata	0.89	1.22	1.05	0.99	1.21
Calabria	1.00	1.58	1.58	1.00	1.12
Campania	0.99	1.06	0.97	0.93	1.05
Emilia-Romagna	1.00	1.09	1.00	0.93	1.09
Friuli-Venezia Giulia	1.00	1.09	1.02	0.94	1.08
Lazio	0.98	1.07	1.01	0.96	1.07
Liguria	0.99	1.16	1.05	0.92	1.16
Lombardy	1.00	1.09	1.02	0.93	1.10
Marche	0.99	1.09	1.01	0.93	1.10
Molise	1.00	1.02	0.95	1.00	1.02
Piedmont	1.01	1.10	1.04	0.94	1.10
Puglia	1.02	1.09	1.09	0.98	1.10
Sardinia	1.00	1.08	1.08	1.00	1.01
Sicily	1.05	1.26	1.40	1.06	1.18
Tuscany	0.99	1.09	1.02	0.94	1.09
Trentino-Alto Adige	1.00	1.07	0.99	0.93	1.07
Umbria	0.99	1.10	1.03	0.95	1.10
Aosta Valley	1.00	1.07	1.07	1.00	1.01
Veneto	1.00	1.12	1.03	0.92	1.10
Overall	1.00	1.13	1.07	0.96	1.09

intensity of the inputs utilized in producing effective results for the regions. The growth in output was, on average, around 100% for all the periods under consideration, with some regions performing better than others. SECH indicates that almost all regions experienced a decrease in productivity, ranging between 4% and 8%. Regarding the magnitude of technological change, all regions underwent technological progress, as indicated by MATC values exceeding 1 (see Table A.2). Overall, the Italian regions are performing well, and their technological innovation is

up to date. These results align with the Italian recycling rate (2010–2019) shown in Fig. 1, indicating the robustness of the analysis framework.

4.3. Robustness Check

This section presents the results of an additional application of intertemporal DEA, aimed at reinforcing and validating the preceding findings. To evaluate the contribution of voluntary environmental policy decisions adopted at a regional level to a green transition within the CE perspective, two additional simulations are conducted using the Gross Domestic Product and Gross Value Added (GDP_GVA) in volume - a composite index based on the 2015 baseline - and Population Density by NUTS 2 region (pop_density), measured in persons per square kilometer. Both indicators are sourced from Eurostat⁵ at the NUTS 2 level, and are considered inputs capable of generating waste.

Table 5 provides the outcomes, including the mean, standard deviation and frequency of instances where the region in question achieved efficiency, from two intertemporal DEA simulations. The first set of results, represented in the “With environmental policy inputs” columns, pertains to a model that includes environmental policies and these two new indicators as inputs. The second set, labeled “Without environmental policy inputs”, presents DEA results from a simulation including only GDP_GVA and pop_density as inputs, without considering environmental policies.

From Table 5, it can be observed that the scores are higher in the DEA model that includes environmental policy inputs. This difference is

Table 5
Efficiency scores of the intertemporal DEA-Bootstrap (2015–2019) – Robustness Check.

DMU	With environmental policy inputs			Without environmental policy inputs			Difference	
	Mean	Std. Dev.	N TE = 1	Mean	Std. Dev.	N TE = 1	Mean	Std. Dev.
Abruzzo	0.76	0.01	0	0.73	0.01	0	0.03	0.00
Basilicata	0.66	0.13	0	0.58	0.01	0	0.08	0.14
Calabria	0.91	0.12	2	0.67	0.02	0	0.24	0.11
Campania	0.99	0.02	4	0.71	0.01	0	0.28	0.02
Emilia-Romagna	1.00	0.01	4	0.99	0.01	4	0.00	0.00
Friuli-Venezia Giulia	0.83	0.02	0	0.76	0.02	0	0.08	0.01
Lazio	0.95	0.04	1	0.78	0.01	0	0.17	0.03
Liguria	0.95	0.01	0	0.83	0.02	0	0.12	0.01
Lombardy	1.00	0.00	5	1.00	0.01	4	0.00	0.01
Marche	0.91	0.02	0	0.82	0.01	0	0.09	0.01
Molise	0.72	0.16	1	0.62	0.02	0	0.10	0.16
Piedmont	0.90	0.07	0	0.77	0.02	0	0.13	0.05
Puglia	0.87	0.05	0	0.72	0.01	0	0.15	0.05
Sardinia	0.99	0.02	4	0.99	0.02	4	0.00	0.00
Sicily	0.90	0.08	1	0.74	0.02	0	0.17	0.07
Tuscany	0.95	0.01	0	0.95	0.01	0	0.00	0.00
Trentino-Alto Adige	0.80	0.02	0	0.79	0.02	0	0.01	0.01
Umbria	0.89	0.02	0	0.84	0.02	0	0.06	0.01
Aosta Valley	1.00	0.01	4	0.98	0.02	2	0.01	0.02
Veneto	1.00	0.01	4	0.77	0.02	0	0.22	0.02
Overall	0.90	0.11	30	0.80	0.12	14	0.10	0.10

⁵ <https://ec.europa.eu/eurostat/databrowser/recent?lang=en&display=list&sortingOption=Both&filterOption=none>

evident in the column measuring the change between the score with and without certification inputs. Furthermore, it is noteworthy that the inclusion of environmental policy inputs leads to a more than twofold increase in the number of technically efficient regions ($TE = 1$), going from 14 to 30.

The regions that demonstrated optimal performance in the baseline model (refer to Table 2) consistently affirm this outcome in both simulations incorporating the new inputs. Notably, two industrially developed and densely populated regions (Emilia Romagna, Lombardia) and two less industrialized and sparsely populated ones⁶ (Sardegna and Valle d'Aosta) exhibit strong performance in both cases.

In the “With environmental policy inputs” simulation, regions such as Calabria, Campania, Lazio, Sicily and Veneto present technically efficient scores that are not replicated in the model without policy inputs. This emphasizes the significant role of voluntary environmental policy decisions adopted at a regional level in facilitating a green transition within the CE perspective.

5. Discussion

The present research contributes to the growing debate on green initiatives and voluntary environmental regulations that seek to achieve sustainable production through resource management and efficient waste management.

The DEA results show an overall rising trend in efficiency among the Italian regions between 2015 and 2019, which indicates greater attention being paid to the sustainable management of resources across the regions. This trend is confirmed by the Malmquist analyses, which show that the regions performed well during the period under consideration. Furthermore, they reveal that technological innovation is adequate, and thus contributes to this efficiency. These results align with the national recycling rate for 2010–2019, indicating the robustness of the analysis framework. This study's results provide useful evidence for policymakers. They enable us to formulate several considerations that are valuable in understanding how to design environmental policies to maximize the efficiency of waste management at the regional level while meeting circular economy goals. It is important to emphasize that the transition to a CE is influenced by several determinants, such as the composition and innovation intensity characterizing a given economy, the evolution, and trends of new green markets and by the environmental and industrial policy settings (Edmondson et al., 2019).

Our research findings have several implications. From a policy perspective, the present study shows how voluntary regulations, represented by certifications such as EMAS and UNI EN ISO 14001, positively affect the waste management system at the regional level, which is a pillar of regional circularity. To promote organizations' transition to CE, policymakers should support the adoption of voluntary green initiatives and regulations, which can also affect the complementarity among technological and organizational innovations. Legislative and financial support, including regulatory relief and incentives, as well as fiscal benefits, should be provided to encourage organizations (both public and private) to adopt EMS standards. Furthermore, by recognizing the importance of EMS standards, policymakers should integrate them into a comprehensive environmental policy. The adoption of the Deming cycle, as seen in EMAS, can be used as a model for designing effective policy instruments. Policymakers should focus on developing regional-level voluntary regulations that specifically target waste recycling efficiency. Lessons from studies such as Johansson and Corvellec (2018) should guide the design of policies that stimulate greater efficiency in waste recycling, fostering a green transition within the CE framework. Finally, policymakers should continue to support and promote technological innovation, as indicated by the Malmquist analyses, to maintain

⁶ See Table A.3 in the Appendix for an overview of input variables employed in the robustness assessment.

and enhance efficiency in resource management. Consequently, initiatives that encourage the adoption of innovative technologies in waste recycling and environmental management should be prioritized.

Our results provide policymakers with information about supporting voluntary approaches that can improve the flexibility and cost effectiveness of the policy mix, and potentially allow for savings in administrative costs. The effectiveness of this “going soft” (Johansson and Corvellec, 2018) in terms of policies shows the limits of the “command-and-control” approach, which has been criticized as being inflexible, limited and cost-ineffective (Ziegler and Nogareda, 2009). On that basis, the implication for policy-making is that, in addition to the application of market-based instruments (e.g. carbon taxes, environmental levies and charges), and legal and economics-related schemes such as liability and non-market ones (e.g. technological standards), attention should be paid to the positive effect of knowledge creation as a source of regulatory efficiency and effectiveness. Voluntary approaches are an important complement in the policy toolkit, especially in realms such as that of circularity where – more than in the energy field – performance is driven by a sum of bottom-up series of inventions and innovation diffusion patterns. The complementarity of voluntary approaches with other tools in the policy mix portfolio deserves greater attention as regards CE (Del Río, 2014). The role of regional knowledge stocks should be emphasized more for policy-making effectiveness. The larger knowledge investments are, the greater the possible role of policy can be in inducing new inventions. The higher the combination of any R&D/human capital sources, including their spillovers, the stronger the socio-technical system capacity can be to absorb the effect of the policy, translating this into inventions (Mazzanti and Musolesi, 2020).

Finally, new business and policy strategies should redesign production and consumption through pervasive technological and behavioural changes. Innovation, intended here as knowledge creation and diffusion throughout territories and value chains (Diaz Lopez et al., 2023), is among the most important factors behind resource productivity. Conceptually, the IPAT identity shows how sustainable-oriented technological development (resource/emissions efficiency of production) can compensate for scale economy-driven effects (Marin and Mazzanti, 2013; York et al., 2003). Technological development and efficiency are thus embedded within the ‘resource productivity’ element, which includes all knowledge-based factors, and are the pillars of decoupling.

The complementarity of voluntary approaches with other tools in the policy mix portfolio deserves increasing attention in the study of circularity. The role of regional knowledge stocks should be more emphasized in policy-making effectiveness. The greater the knowledge investments are, the greater will be the possible role of policy in inducing new inventions. The higher the combination of any R&D/human capital sources, including their spillovers, the greater will be the socio-technical system's capacity to absorb the effects of the policy, translating this into inventions.

6. Conclusions

The aim of the present study is to identify if voluntary environmental policy decisions adopted at a regional level, in a country which presents strong policy decentralization (environmental federalism), contribute to a green transition from the perspective of the CE. This innovation-based production strategy emphasizes reducing environmental impact and waste, and optimizing the performance and efficiency of the processes involved, which may bring about unexplored economic opportunities to support economic growth (Ghisellini et al., 2016; Witjes and Lozano, 2016).

By applying DEA, this study has considered general and region-specific trends of waste management and environmental certifications in Italy, and compared the performance of the 20 regions in the period 2015–2019, showing that voluntary regulations improved the efficiency of waste recycling (Ziegler and Nogareda, 2009). This approach allows us to examine regional perspectives, efforts and opportunities for the

advancement of the CE with a specific focus on waste management. A further investigation, exploiting the panel characteristics of the data, involves Malmquist analysis (Färe et al., 1989, 1992) to evaluate the efficiency of all DMUs in terms of productivity growth. The DEA results show an overall rising trend of efficiency among the Italian regions. This trend is supported by the MPA, which confirms that the regions performed well during the period under consideration. Furthermore, they reveal that technological innovation in Italian waste management contributes to greater efficiency in socio-economic systems which are characterized by ‘environmental federalism’. This study also has implications for firms. Given that waste management in the form of recycling is a direct way to apply the CE, as it is a pillar of broader waste reduction, firms should pay more attention and dedicate more resources to this topic. Our findings provide various implications in terms of potential development opportunities to pursue in different European contexts. Future studies could investigate how CE practices can be effectively embedded into the social system in which firms and public administrations operate, as it is not yet sufficiently evident what kinds of impact on social dynamics may be generated by implementing CE practices. This study is explorative in nature, demonstrating the general trends registered for the Italian regions over a limited timeframe. This analysis possesses various inherent limitations. First, the choice of waste management indicators, constrained by data availability, may have introduced a bias towards favoring recycling, potentially influencing the results obtained. Moreover, the analysis does not account for the possibility of waste exchange between regions, which could have an impact on the outcomes. To accurately capture the evolutionary patterns and efficiency drivers of the CE, it is important to compare various inputs and outputs, and to properly characterize their relationships. Replicating the study in different European regions would yield valuable insights and contribute to validating and confirming the findings, serving as a crucial step towards ensuring the robustness of the research.

While prior research on CE has focused on the regulatory policies of different countries and regions, our study has shown that the support of such regulations is fundamental, but these regulations are not sufficient on their own. Therefore, more research is required to demonstrate how the CE and voluntary policy tools can positively affect organizations'

opportunities and increase the efficiency of waste management. Future research should use this article's two-step analysis on a panel of Italian municipalities and provinces and replicate the analysis in other European and extra-European countries characterized by environmental federalism. Another interesting future research topic is the complementary impacts of mandatory and voluntary programs and schemes on organizations' environmental strategies and performance, rather than analyzing their influence separately (Aragón-Correa et al., 2020).

CRedit authorship contribution statement

Marta Meleddu: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Writing – original draft, Writing – review & editing. **Marilena Vecco:** Conceptualization, Funding acquisition, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Massimiliano Mazzanti:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

Data availability

Data will be made available on request.

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Appendix

Table A.1.

DMU	2015		2016		2017		2018		2019	
	Scale	RTS	Scale	RTS	Scale	RTS	Scale	RTS	Scale	RTS
Abruzzo	0.76	irs	0.68	irs	0.65	irs	0.62	irs	0.57	irs
Basilicata	1.00	irs	1.00	–	0.92	irs	0.71	irs	0.72	irs
Calabria	1.00	–	1.00	–	1.00	–	1.00	–	1.00	–
Campania	1.00	–	1.00	–	0.96	drs	0.83	drs	0.71	drs
Emilia-Romagna	0.87	drs	0.71	drs	0.67	drs	0.65	drs	0.64	drs
Friuli-Venezia Giulia	0.78	irs	0.78	drs	0.69	irs	0.62	irs	0.60	drs
Lazio	0.77	drs	0.77	drs	0.71	drs	0.68	drs	0.63	drs
Liguria	0.78	drs	0.65	drs	0.62	drs	0.53	drs	0.55	drs
Lombardy	0.75	drs	0.72	drs	0.62	drs	0.58	drs	0.56	drs
Marche	0.81	drs	0.76	drs	0.69	drs	0.67	drs	0.61	drs
Molise	1.00	–	0.99	irs	1.00	–	1.00	–	0.94	irs
Piedmont	0.76	drs	0.67	drs	0.69	drs	0.64	drs	0.59	drs
Puglia	0.81	drs	0.75	drs	0.78	drs	0.76	drs	0.72	drs
Sardinia	1.00	–	1.00	–	1.00	–	1.00	–	1.00	–
Sicily	0.70	drs	0.60	drs	0.63	drs	0.72	drs	0.85	drs
Tuscany	0.68	drs	0.64	drs	0.59	drs	0.55	drs	0.54	drs
Trentino-Alto Adige	0.84	irs	0.67	irs	0.66	irs	0.63	irs	0.63	irs
Umbria	0.78	irs	0.76	drs	0.73	irs	0.65	irs	0.63	drs
Aosta Valley	1.00	–	1.00	–	1.00	–	1.00	–	1.00	–
Veneto	0.82	drs	0.84	drs	0.78	drs	0.62	drs	0.58	drs
ITALY	0.85		0.80		0.77		0.72		0.70	

Table A.2
Efficiency change by DMU (2015–2019).

DMU	Pdwise	TECH	TECCH	TFPCH	SECH	MATC
Abruzzo	2015–2016	1.00	1.20	1.08	0.89	1.20
Abruzzo	2016–2017	0.97	1.04	0.96	0.96	1.04
Abruzzo	2017–2018	0.99	1.04	0.98	0.95	1.04
Abruzzo	2018–2019	0.99	1.01	0.91	0.91	1.00
Basilicata	2015–2016	0.73	1.25	1.17	1.28	1.23
Basilicata	2016–2017	0.90	1.52	1.27	0.93	1.45
Basilicata	2017–2018	0.94	1.10	0.78	0.75	1.14
Basilicata	2018–2019	0.98	1.01	1.00	1.01	1.01
Calabria	2015–2016	1.00	1.60	1.60	1.00	1.31
Calabria	2016–2017	1.00	1.93	1.93	1.00	1.15
Calabria	2017–2018	1.00	1.32	1.32	1.00	1.00
Calabria	2018–2019	1.00	1.46	1.46	1.00	1.03
Campania	2015–2016	1.00	1.05	1.05	1.00	1.05
Campania	2016–2017	1.00	1.01	0.97	0.96	1.00
Campania	2017–2018	1.00	1.10	0.96	0.87	1.11
Campania	2018–2019	0.96	1.06	0.91	0.89	1.06
Emilia-Romagna	2015–2016	1.00	1.23	1.01	0.82	1.23
Emilia-Romagna	2016–2017	1.00	1.04	0.97	0.93	1.04
Emilia-Romagna	2017–2018	1.00	1.06	1.04	0.98	1.06
Emilia-Romagna	2018–2019	1.00	1.01	0.99	0.98	1.01
Friuli-Venezia Giulia	2015–2016	1.02	1.11	1.13	0.99	1.10
Friuli-Venezia Giulia	2016–2017	0.99	1.10	0.97	0.89	1.10
Friuli-Venezia Giulia	2017–2018	1.01	1.11	0.99	0.89	1.09
Friuli-Venezia Giulia	2018–2019	0.99	1.04	1.01	0.98	1.04
Lazio	2015–2016	1.00	1.11	1.11	1.01	1.12
Lazio	2016–2017	0.94	1.03	0.89	0.92	1.03
Lazio	2017–2018	1.00	1.08	1.04	0.96	1.09
Lazio	2018–2019	0.99	1.06	0.98	0.94	1.06
Liguria	2015–2016	1.00	1.29	1.07	0.83	1.31
Liguria	2016–2017	1.00	1.15	1.11	0.96	1.13
Liguria	2017–2018	0.97	1.18	0.97	0.85	1.18
Liguria	2018–2019	1.00	1.04	1.07	1.03	1.03
Lombardy	2015–2016	1.00	1.20	1.16	0.96	1.21
Lombardy	2016–2017	1.00	1.07	0.91	0.86	1.07
Lombardy	2017–2018	1.00	1.06	1.00	0.94	1.06
Lombardy	2018–2019	1.00	1.03	1.00	0.96	1.04
Marche	2015–2016	1.01	1.15	1.09	0.94	1.17
Marche	2016–2017	0.99	1.09	0.98	0.90	1.09
Marche	2017–2018	1.00	1.09	1.07	0.98	1.07
Marche	2018–2019	0.97	1.05	0.91	0.90	1.05
Molise	2015–2016	0.92	1.04	0.99	1.03	1.04
Molise	2016–2017	1.47	1.03	1.09	0.72	1.03
Molise	2017–2018	0.65	1.00	0.88	1.35	1.00
Molise	2018–2019	0.94	1.00	0.85	0.90	1.00
Piedmont	2015–2016	0.96	1.18	0.99	0.88	1.19
Piedmont	2016–2017	1.05	1.04	1.13	1.03	1.06
Piedmont	2017–2018	1.05	1.10	1.09	0.94	1.09
Piedmont	2018–2019	0.98	1.06	0.94	0.90	1.06
Puglia	2015–2016	1.01	1.18	1.11	0.93	1.21
Puglia	2016–2017	1.03	1.05	1.12	1.05	1.05
Puglia	2017–2018	1.03	1.09	1.09	0.97	1.09
Puglia	2018–2019	1.03	1.06	1.05	0.97	1.06
Sardinia	2015–2016	1.00	1.11	1.11	1.00	1.00
Sardinia	2016–2017	1.00	1.12	1.12	1.00	1.04
Sardinia	2017–2018	1.00	1.04	1.04	1.00	1.02
Sardinia	2018–2019	1.00	1.03	1.03	1.00	1.00
Sicily	2015–2016	1.04	1.34	1.20	0.86	1.29
Sicily	2016–2017	1.15	1.44	1.75	1.06	1.13
Sicily	2017–2018	1.00	1.22	1.38	1.13	1.23
Sicily	2018–2019	1.00	1.05	1.25	1.19	1.05
Tuscany	2015–2016	1.00	1.23	1.15	0.94	1.23
Tuscany	2016–2017	0.97	1.04	0.94	0.93	1.04
Tuscany	2017–2018	1.00	1.06	0.98	0.92	1.06
Tuscany	2018–2019	1.00	1.01	0.99	0.98	1.01
Trentino-Alto Adige	2015–2016	1.00	1.21	0.96	0.80	1.20
Trentino-Alto Adige	2016–2017	1.00	1.04	1.04	1.00	1.04
Trentino-Alto Adige	2017–2018	1.02	1.04	0.98	0.92	1.04
Trentino-Alto Adige	2018–2019	0.99	1.00	0.99	1.00	1.00
Umbria	2015–2016	1.01	1.13	1.12	0.98	1.13
Umbria	2016–2017	0.95	1.12	1.02	0.95	1.11
Umbria	2017–2018	1.00	1.13	1.00	0.88	1.13
Umbria	2018–2019	0.99	1.03	0.99	0.98	1.03
Aosta Valley	2015–2016	1.00	1.11	1.11	1.00	1.00
Aosta Valley	2016–2017	1.00	1.14	1.14	1.00	1.02

(continued on next page)

Table A.2 (continued)

DMU	Pdwise	TECH	TECCH	TFPCH	SECH	MATC
Aosta Valley	2017–2018	1.00	1.01	1.01	1.00	1.00
Aosta Valley	2018–2019	1.00	1.01	1.01	1.00	1.01
Veneto	2015–2016	1.00	1.14	1.18	1.03	1.11
Veneto	2016–2017	1.00	1.11	1.03	0.93	1.07
Veneto	2017–2018	1.00	1.19	0.94	0.79	1.18
Veneto	2018–2019	1.00	1.05	0.99	0.94	1.05

Table A.3

Summary of input variables for robustness check.

DMU	GDP_GVA		pop_density	
	Mean	Std. Dev.	Mean	Std. Dev.
Abruzzo	100.74	0.59	122.70	1.96
Basilicata	102.96	2.09	57.40	1.56
Calabria	99.34	0.55	130.30	3.18
Campania	101.28	1.07	430.04	6.60
Emilia-Romagna	103.40	2.48	200.28	1.95
Friuli-Venezia Giulia	101.76	1.94	160.90	0.82
Lazio	103.06	1.85	347.06	2.36
Liguria	101.00	0.74	290.08	4.84
Lombardy	103.58	2.61	436.98	1.88
Marche	101.88	1.51	163.38	1.03
Molise	102.20	2.00	69.92	1.40
Piedmont	103.10	2.31	174.94	2.24
Puglia	101.38	1.05	210.24	2.38
Sardinia	98.98	0.95	69.10	0.47
Sicily	100.06	0.42	196.58	3.27
Tuscany	102.54	2.44	164.20	1.12
Trentino-Alto Adige	103.62	3.31	79.57	0.45
Umbria	101.04	1.54	106.94	1.12
Aosta Valley	100.18	1.34	39.02	0.35
Veneto	103.26	2.33	281.44	1.55
Total	101.77	2.16	186.55	114.84

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