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Review

The circular economy implementation at the European Union level. Past, present and future

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ABSTRACT

Shifting from a traditional linear to an alternative circular paradigm can foster economic growth and support sustainable capital renewal in the European Union. This topic has attracted growing academic interest in recent years. However, the evaluation of case studies regarding Circular Economy implementation, strategies, and practices (at all levels) is still in its infancy. With the aim of bridging this gap, this paper analyses, through a systematic review of case studies, the implementation of circular practices in all economic sectors and industries of the European Union (from 2015 until April 2023). To this end, this research uses a framework of circular strategies built considering the European Union political framework. Based on this analysis, it can be deduced that recycling was the most used circular strategy (24.2%) to reintegrate materials into the economic system and reduce the use of raw materials (18.9%), demonstrating the existence of virtuous circles in the European Union's economic sectors. The results show that the best performing industry, in terms of circular strategies, is Food and Beverage (17.92%), within the Agri-food economic sector. While the economic sector with the least number of circular strategies (7.86%) is Capital Equipment. This paper proposes several tools for Circular Economy implementation that could lead to future research and support business, policymakers, and the scientific community.

1. Introduction

One of the hardest challenges facing modern societies is the scarce availability of resources. This condition is intensified by the large amount of waste produced. A paradigm shift is therefore needed to ensure that resources are used more efficiently. This implies a rethinking of processes so that resources are used more effectively and within a closed-loop system (Morone and Yilan, 2020).

Circular Economy (CE) features prominently on international political and governmental agendas, particularly in Europe (Brennan et al., 2015; EC, 2015; EC, 2020a). It is an enabling factor for economic development, able of creating employment, enhancing new businesses, promoting security of supply, reducing costs, waste, and environmental burdens (Kalmykova et al., 2018).

Within the framework of the European Union (EU), all EU countries have launched a series of policies to support circularity. This is also in line with academic research on CE performance in the EU, which presents several findings regarding its implementation at all levels (micro, meso and macro), across various economic sectors and EU countries (Boffardi et al., 2021). Furthermore, the European Commission (EC) has recently defined the guidelines of Industry 5.0 which, contrary to the Industry 4.0 paradigm, is based on human well-being and progress, shifting production and consumption towards a more sustainable, circular and regenerative approach, as stayed by the Green Deal. Therefore, the transition to the CE is now inevitable.

However, there are still some knowledge gaps in identifying circularity approaches, CE strategies, and its implementation in various sectors (Mhatre et al., 2021). It follows that, in the context of the growing research on CE implementation the open questions are still different.

In this perspective, the literature underlines how the demand for a more consistent circular behavior is increasing among policymakers, companies, industries, experts, citizens, scholars, and national governments.

Indeed, the detection of challenges and constrains to CE

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implementation is recently ushering in a new stream of literature (i.e., Kirchherr et al., 2018; Masi et al., 2018; De Pascale et al., 2021; Hamam et al., 2023). However, it seems that scholars have mainly focused on market, cultural, technological, and regulatory challenges, and barriers (Kirchherr et al., 2018). Thus, a study of factors influencing the transition to CE that specifically consider stakeholder and investor viewpoints (as challenges) and barriers (as obstacles) is still marginal.

On the other hand, numerous barriers can hinder CE implementation. Lieder and Rashid (2016) have singled out some obstacles preventing CE implementation, i.e., the lack of knowledge, financial resources, or the necessary conviction to implement circularity. Battilana et al. (2009) talked about resistance to change, and de Jesus and Mendonça (2018) underlined the lack of effective solutions to promote CE. Likewise, with reference to CE assessment, the existing literature explains how the numerous assessment methods do not consider the most recent developments in the different economic sectors (Coenen et al., 2020) showing gaps due to the different approaches used in this field (De Pascale et al., 2021). Harris et al. (2021) speak of these weaknesses as a search for "*circularity for its own sake*".

Conversely, there is growing interest in using the case studies as a model to evaluate the progress of the CE considering both legislation and economic interests (Arruda et al., 2021). Indeed, Kalmykova et al. (2018) use 100 case studies to provide tools for CE implementation. Mhatre et al. (2021), presents an analysis of case studies to analyze the implementation of circular practices in the EU member countries. However, no studies have yet been developed on building a circular strategy framework based on the EU legislative agenda in order to evaluate CE adoption strategies and practices within the EU economic sectors. This knowledge gap precludes the initiation of useful CE implementation actions, with potentially raised risks to possible CE investments, thus inhibiting potential investors (Kalmykova et al., 2018).

Against this background, this paper aims to answer the following research questions:

#RQ1. Considering the current EU policy framework on the development of CE, what is the actual level of CE implementation in the different EU countries?
#RQ2. What are the categories of actors involved in CE implementation and the benefits of this implementation?
#RQ3. What are the barriers that currently preventing CE implementation in the EU?
#RQ4. What are the economic sectors that have contributed most to the CE implementation in the EU?
#RQ5. And secondly, how is the level of CE implementation measured in the different EU economic sectors?

To this end, this study adopts the definition provided by Kirchherr et al. (2017, p. 224) in which CE is described as "*an economic model based on sharing, lending, reusing, repairing, upgrading and recycling, in a closed loop, which aims to maintain maximum utility and value of products, components and materials in production/distribution and consumption processes, operating at micro, meso and macro levels, with the aim of achieving sustainable development, which implies creating environmental quality, economic prosperity and social equity, at all times*". This definition is in line with the main objective of this research, which is to analyze the economic sectors of the EU. Accordingly, we intended to highlight the concept of "economic model" and economic prosperity, i.e., how CE aims to maintain, protect, transform and/or strengthen the economy.

In this perspective, this paper aims to create transparency regarding the current level of CE implementation at EU level. It explores aspects of CE implementation, through the identification of circularity practices from 2015 (when the European Commission launched the first CE Action Plan) until April 2023, considering both challenges and obstacles. In more detail, this study intends to investigate which economic sectors have contributed (and are contributing) to CE implementation in EU, embracing the challenges of circularity with a gaze on the Green Deal and the EU policy framework. Secondly, it seeks to respond to the need to identify which methodologies and tools are used in the EU to measure CE implementation in the economic sectors.

Accordingly, a perspective based on the CE value chain was adopted to evaluate which economic sector is more developed respect to other economic sectors, and to give useful information about the direction of CE development and on the adopted measurement approaches.

Compared to what has already been published, this paper offers an overall vision on the CE implementation in the EU, in accordance with Elliot (2016). It provides reflections for policymakers, guidelines on investments in sustainability, especially in the post-Covid-19 future, and offers a vision of the assessment methods for measuring CE implementation, without neglecting the barriers that still prevent its advance.

While all these aspects have so far been addressed by the literature as separate topics, this paper offers an opportunity to create synergies from the intersection of all these features.

Hence, this paper is structured in six sections. Section 2 introduces the conceptual framework of this study. Section 3 presents the research methodology. The remaining sections present the results (Section 4) and provides a discussion (Section 5); finally, Section 6 closes by summarizing the research contribution, impacts, limitations, and future research agenda to address future research needs.

2. Conceptual framework

The analytical perspective used to construct the conceptual framework of this research starts from the definition of the current EU policy framework. This will allow to outline the framework from which to evaluate the level of CE implementation in different EU countries and answer the first research question (#RQ1), as well as develop the answer to #RQ4 research question. Secondly, the role of the actors involved in the CE implementation agenda will be assessed, considering both stakeholder and investor points of view (as challenges) and barriers (as obstacles).

2.1. Overview of CE policy in the EU

CE implementation can generate potential economic and environmental benefits and social wellbeing (EMAF, 2020). The EC tends to encourage a sustainable economic growth, promoting employment and innovation. The European Green Deal (EC, 2019a) supports these challenges with the objective of converting the EU into a prosperous, modern, and fair economy, efficient in using resources and reducing greenhouse gases (GHGs).

In this perspective, on 11th March 2020, the EC launched the new CE Action Plan (EC, 2020a) in line with the Renewed Industrial Strategy for Europe (EC, 2020b) and building on the 2015 Action Plan (EC, 2015). The new CE Action Plan proposes measures to establish a strategic framework focused on the value chain, waste reduction, efficient functioning of the EU internal market for secondary raw materials and aims to generate important economic benefits, environmental and social. Attention is paid to sustainable products (EC, 2019b); empowering consumers and public buyers; attention to sectors with the greatest use of resources such as: ICT and electronics devices; batteries and automobiles; packaging; plastic (Directive (EU) 2019/904); fabrics; construction and building; water and nutrients; food and waste reduction (Directive (EU) 2018/851; EC, 2007).

While, as far as the agricultural sector is concerned, the "Farm to Fork" strategy, launched in May 2020, represents the first attempt at a European-wide approach for a coherent, harmonized, and sustainable food system across the EU (Mowlds, 2020).

In line with the provisions of the New Industrial Strategy, European industry must take a key position in leading the move towards circular models. This requires the integration of CE strategies into all sectors of the European economy.

Furthermore, a circular approach can lead to a more competitive and environmentally friendly European economy, thanks to its potential to create (around) 700,000 new jobs (many of them in small and medium enterprises –SMEs-) and leading to an increase in GDP of about 0.5% by 2030 (EC, 2018; EC, 2020a). On the other hand, EMAF (2017), states that the EU, by 2025, has the potential to generate CE investments in specific sectors, such as: mobility (135 billion euros), construction (115 billion euros); agri-food sector (70 billion euros), for a total of 320 billion euros.

On the other hand, the "Farm to Fork" strategy thanks to its ambitious goals can provide a huge opportunity to transform Europe's rural landscapes from an economic, social, and environmental perspective. In detail, EU member countries could see an increase in biological land and biodiversity. Consumers could see a reduction in food-related greenwashing on shelves and other fraudulent activities. While, farmers could see higher yields, greater bargaining power and start new business opportunities (e.g., in the bioeconomy or plant protein sectors) (Mowlds, 2020).

These data confirm that it is possible to increase resource efficiency, reduce environmental impacts and increase employment (EC, 2005).

The COVID-19 pandemic has shown the weakness of current health protection models, but also of nature, the economy and work (due to restrictions and various lockdowns). This has also spilled over into the food sector, determining new consumption models (e.g., increase in food deliveries, or the use of single-use packaging on a large scale, etc.) and causing the production of enormous quantities of plastic waste, mainly due to food packaging (Kochańska et al., 2021).

The EC has planned an important COVID-19 recovery plan (EC, 2020c) to enhance the EU economic self-sufficiency and to facilitate the shift to a long-term green (EMAF, 2020) and digital economy (EC, 2020d), with the aim of guaranteeing a resilient and regenerative economy (EC, 2020e).

2.2. Perceived challenges in CE implementation

To analyze the challenges related to CE implementation, the stakeholders and investors' perspective, as well as the barriers to prevent CE implementation are examined below. This approach will allow to answer research questions #RQ2 and #RQ3 regarding the definition of actors and barriers.

2.1.1. The stakeholder perspective

The transition to an CE includes assessing the role of stakeholders (policymakers, academics, business, consumers, etc.) (Ghinoi et al., 2020). This aspect has been emphasized in the literature to accelerate the change towards a CE (Chiappetta Jabbour et al., 2020; Ghinoi et al., 2020). For example, Russell et al. (2019) highlighted the pressure from stakeholders to adopt circularity in the EU, but also in regional and national governments, administrative units, and industries (Genovese et al., 2017). However, the most significant role in CE implementation is the policy maker (Opferkuch et al., 2021). For the purposes of this study, three categories of stakeholders have been identified, according to the definition of EMAF (2015):

a) *Policymakers* (policymakers at all government levels – municipal, regional, national, and supranational level-; government agencies; representatives from different government departments; policy and economic experts; etc.).
b) *Businesses* (individual businesses; industry associations; etc.).
c) *Other society stakeholders* (citizens and consumers; labor and environmental organizations/associations; researchers and academics; representatives and unions).

2.1.2. The sustainable capitals and investors' perspective

The idea that CE should follow sustainable development has aroused the interest of both scholars and professionals, because it is considered a virtuous practice of economic sectors aspiring to achieve sustainable goals (Vinante et al., 2020). According to EC the Green Deal and Industry 5.0 represented an important chance to initiate a more resilient economic growth with low GHGs. The CE approach can generate natural, economic, and social capital (Moraga et al., 2019; EAMF, 2020). Meadows (1998) has suggested a framework for assessing sustainability capitals and their interrelationships, including natural, economic (financial and built), and social capital. Accordingly, a framework based on sustainable development capitals is adopted to investigate the investors' perspective, as also demonstrated by Biasi et al. (2019) and Silva et al. (2020).

Natural capital could be considered the origin of this framework because the economic system operates within the environmental system. It is considered as a stock of economic resources (Meadows, 1998). Natural capital represents the availability of resources, but also their use, renewal, and conservation (DesRoches, 2018). It can be evaluated through the recycling of resources, or in terms of actions capable of preventing its qualitative degradation or increasing its environmental benefits (Silva et al., 2020). if waste is recovered, recycled, and reused, it can be interpreted as an investment in natural capital (because these practices reduce its exploitation). Otherwise, waste must be considered as consumption or depreciation of natural capital (Ekins, 2003).

Economic capital needs natural raw materials, labor, and governance to create products/services to satisfy consumers' needs (Meadows, 1998), while sustainability requires verifying whether economic capacity and investments can satisfy both current and long-term demand. Accordingly, economic capital grows if the investments for its conservation are greater than its obsolescence and depreciation. This helps to stimulate other forms of investment and reduce the demand for capital replacement (Van den Belt et al., 2013). Conversely, the lack of investment and finance can (also) cause a deceleration in CE implementation and become an obstacle, especially for SMEs (Lanfranchi et al., 2023; Aranda-Usón et al., 2019).

Social capital represents the intangible assets available for a community (Meadows, 1998). In terms of human capital, it can be described by the relationships between rational stakeholders, who acting as economic actors and use their social relationships to obtain materials and resources (Kwok et al., 2019). In terms of workforce, it also depends on the levels of education and health of a community and constitutes a production factor that contributes together with economic and natural capital to create value (Anand and Sen, 2000).

2.3. Perceived barriers in CE implementation

Despite the many benefits of transitioning to a CE, several barriers have been identified in the literature. These obstacles range from the structural to social level. More specifically, Grafström and Aasma (2021) and Kirchherr et al. (2018) identified 4 types of barriers:

a) *Technological barriers.* Ascribable to design, lack of know-how (especially in SMEs) or new technologies, and to the poor quality (perceived or real) of the recycled products/materials both by producers (who in many cases continue to prefer virgin materials) and by consumers.
b) *Market barriers.* Market failure (externalities are not internalized) or lack of market, but also obstacles related to lack of funding for circular business models, high implementation costs and low prices of virgin raw materials (Masi et al., 2018).
c) *Institutional (and regulatory) barriers.* Caused by growing global economic interconnections, different political approach between different countries, and lack of physical infrastructure for reverse logistics.
d) *Social (and cultural) barriers.* Non-change-oriented corporate culture, poor consumer awareness of products circularity, and reduced collaboration along the value chain.

Fig. 1 describes the conceptual framework of challenges and barriers

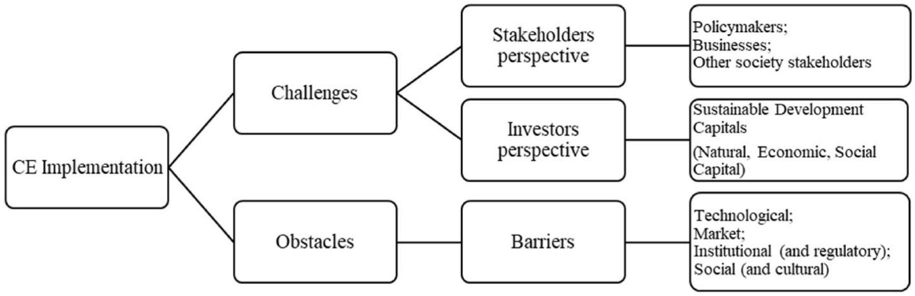

Fig. 1. Evaluation of CE implementation.

to CE implementation proposed in this study. It takes into consideration the challenges and constraints (barriers) and, in doing so, analyzes two perspectives (stakeholders and investors) connected to the CE implementation, to identify the CE actors and rank the possible benefits deriving from the adoption of circular strategies, considering the EU policy framework. The necessity to consider the political framework arises from the consideration that policy can represent both a barrier and an enabling factor of CE implementation (Rizos and Bryhn, 2022).

3. Research methodology

To identify CE actors and rank the possible benefits deriving from the adoption of circular practices at EU level, a literature screening was conducted with the aim of identifying case studies and practices applied in the EU from the 2015 to April 2023 and covered by the literature on the subject. The bibliographic search was conducted on scientific databases (Scopus, ScienceDirect and Web of Science Core Collection) using the keywords "Circular Economy AND Case Stud* AND Assessment AND European Union".

A total of 1080 articles were obtained and thirty-four case studies

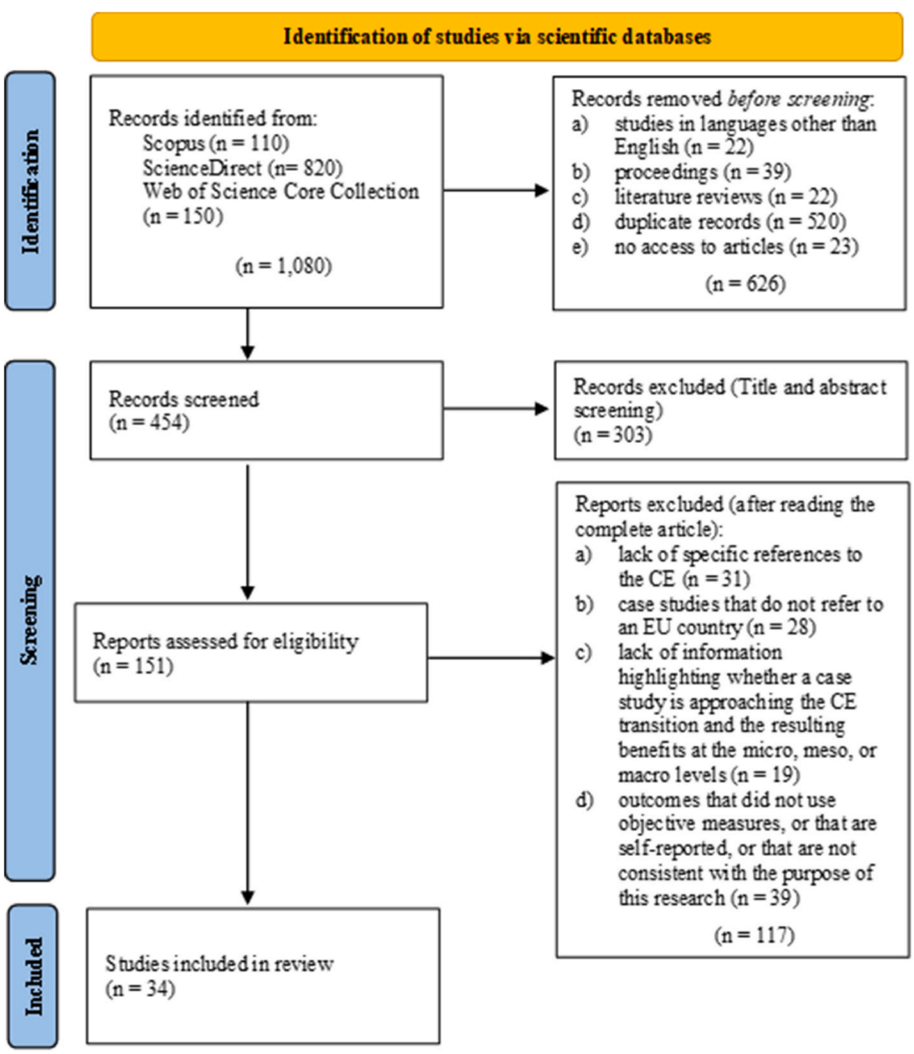

Fig. 2. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) diagram showing the screening process (http://www.prisma-statement.org).

(representative of different EU countries and concerning the implementation of CE practices). The screening process focused only on research articles and therefore included only formal literature and peer-reviewed articles. Consequently, proceedings were excluded from this study, consistent with Mhatre et al. (2021), Aruda et al. (2021) and Geissdoerfer et al. (2020). Additionally, literature reviews were excluded consistent with the goal of this search, which focused on reviewing case studies. The screening process can be seen in Fig. 2.

These case studies were summarized in a framework representing the distribution over time (Fig. 3).

The 34 case studies were classified into macro, micro, and meso, according to Kirchherr et al. (2017) and including the supply chain (Cottafava and Ritzen, 2021).

Furthermore, considering the purpose of this research, that is to identify the way in which the various economic sectors are implementing CE, the 34 case studies have been assigned to the various economic sectors and industries through the classification supplied by the Circle Economy database (CIRCLELab) and Pieroni et al. (2019). Accordingly, six economic sectors and twelve industries involved in the CE implementation processes have been identified.

For better data management and allow for later cross-referencing, the economic sectors and industries have been indexed with a code (i.e., [MF] has been used for the economic sector "Materials and Fuels").

Table 1 offers a summary of the selected case studies; a detailed overview is offered in the Appendix A.1.

A second step concerned the identification of the EC strategies adopted, in the 34 selected case studies, to embrace the various steps of the CE value chain. In this regard, the value chain CE proposed by Accenture Strategy (2014) and Kalmykova et al. (2018) is used. Fig. 4, describes the eight steps that make up the CE value chain, including the main flows of material resources in the EU, according to Eurostat (2021).

In order to allow for cross-comparisons in subsequent stages and to adapt the different steps to CE strategies, the various steps were indexed using the description of the step name and a code (i.e., A. Raw materials).

4. Results

The CE strategies were identified using the methodology offered by Kalmykova et al. (2018) and by Elia et al. (2017). These strategies have been integrated both with the existing literature and with the European regulatory context. Thus, each strategy has been assigned to the corresponding stage of the CE value chain (Table 2). These three phases will allow to obtain, as shown in the following sections, an analytical framework useful for analyzing the two challenges perspectives: stakeholders, and investors (related to the sustainable capital perspective) and identifying the barriers associated to the CE implementation in the EU.

They also help to provide a general understanding of the level of the CE implementation in the EU.

5. Discussions

In the following sections, in line with the aim of this study, which explores CE implementation, investigating which economic sectors have contributed (and are contributing) to this paradigm shift in the EU, we proceed to answer the five research questions. To answer the first general research question: "#RQ1: Considering the current EU policy framework on CE development, what is the actual level of CE implementation in different EU countries?" the challenges in terms of benefits are first presented and the barriers are classified. Finally, coming to the representation of the economic sectors that have contributed (and are contributing) to CE implementation in the EU. As well as showing how CE implementation is assessed.

5.1. Challenges

According to the aim of this study, the stakeholders and investors' viewpoints act a crucial role in stimulating the shift towards the CE implementation. The following sections evaluate these perspectives as feasible tools to promote a CE transition and with the aim of answering the question "#RQ2. What are the categories of actors involved in CE implementation and the benefits of this implementation?".

5.1.1. The stakeholders' perspective

Since stakeholders occupy an important position in the CE implementation and, consequently, they can act as enablers (Russell et al., 2019), it is assumed that their presence and influence positively drive the CE implementation and inhibit the barriers. Indeed, the evolution to a circular model requires a governance perspective capable of predicting all the relationships established along the value chain, within the various economic sectors, and between all stakeholders. Accordingly, Table 3 highlights the role of stakeholders, extrapolated from the 34 case studies, in CE implementation. As already mentioned, three categories of stakeholders have been identified: policymakers, businesses, other society stakeholders.

Although all categories of stakeholders are appropriately represented, it emerges that the most influential groups are: "Legislators" (f_i

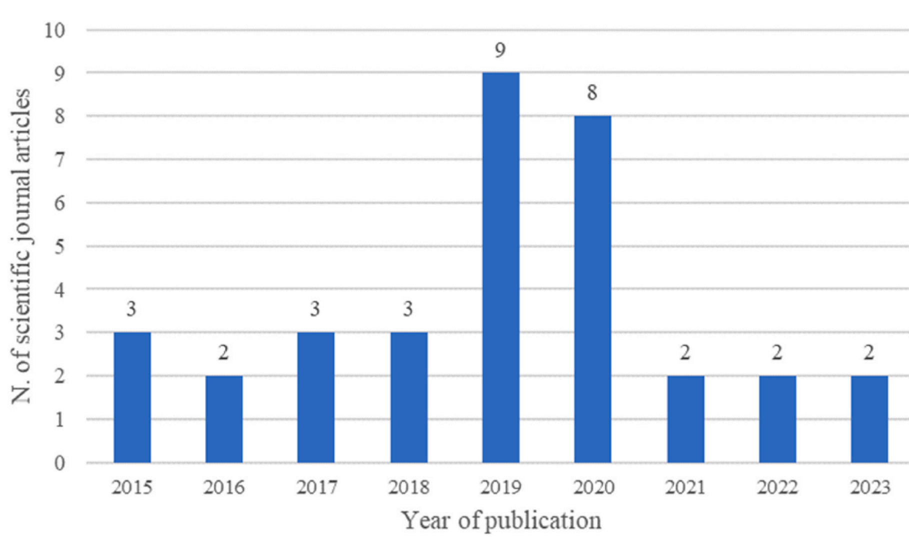

Fig. 3. The distribution of the analyzed scientific journal articles per year (2015–2023).

Table 1
Reviewed literature.

N.	References	Implementation level	Economic sectors			Circularity challenges
			Economic Sector Classification	Industry	Specialization	
1	Strazza et al. (2015)	Meso	Agri/Food [A/F]	Food and Beverage [FB]	Feed production	Converting food waste from cruise ships into feed.
2	Di Maio and Rem (2015)	Micro	Materials and Fuels [MF]	Metal and Glass [MG]	Recycling car materials	Product circularity assessment.
3	Huysman et al. (2015)	Micro	Materials and Fuels [MF]	Chemical and Plastic [CP]	Plastic waste recycling	Resource efficiency assessment and its implementation in European product policies.
4	Husgafvel et al. (2016)	Meso	Materials and Fuels [MF]	Wood and Paper [WP]	Symbiosis products	Environmental impact assessment for a symbiotic product.
5	Jiménez-Rivero and García-Navarro (2017)	Micro/Meso (Supply Chain)	Construction and Infrastructure [CI]	Construction Materials and Products [CMP]	Gypsum plasterboard	Environmental impacts of plasterboard recycling.
6	Daddi et al. (2017)	Meso	Goods and Services [GS]	Fashion and Textiles [FT]	Tannery cluster	Industrial Symbiosis (IS) in a cluster of SMEs.
7	Fregonara et al. (2017)	Micro	Construction and Infrastructure [CI]	Construction Materials and Products [CMP]	Frame window; Decision-makers	Proposal of a planning methodology to support decisionmakers.
8	Huysman et al. (2017)	Micro	Materials and Fuels [MF]	Chemical and Plastic [CP]	Post-industrial plastic waste; Decision-makers	Circular efficiency of plastic waste treatments.
9	Hutner et al. (2018)	Macro	Societal Services [SS]	Waste Management [WM]	Waste Management	Waste prevention.
10	Richter et al. (2018)	Micro	Goods and Services [GS]	Electronics and Appliances [EA]	Energy saving lamp manufacturers	Optimal life of energy saving lamps.
11	Vanegas et al. (2018)	Micro	Capital Equipment [CE]	Electrical and Electronic Equipment [EEE]	LCD-Monitor	Optimal product disassembly.
12	Kaddoura et al. (2019)	Micro	Goods and Services [GS]	Retail [R]	Passive Durable Products	Durability of products.
13	André et al. (2019)	Micro	Goods and Services [GS]	Electronics and Appliances [EA]	Electronics and Appliances	Environmental impacts of used electronic equipment, and its commercial reuse.
14	Bech et al. (2019)	Micro	Goods and Services [GS]	Fashion and Textiles [FT]	Fashion and Textiles	Environmental aspects connected to a Use-oriented product-business model in the textiles industry.
15	Cervo et al. (2019)	Meso	Construction and Infrastructure [CI]	Construction Materials and Products [CMP]	Industrial clusters	Removal of IS barriers
16	Scarpellini et al. (2019)	Macro	Societal Services [SS]	Education and Government Services [EGS]	Whole society at regional level	CE implementation at regional level
17	Gigli et al. (2019)	Micro/Meso (Supply Chain)	Materials and Fuels [MF]	Chemical and Plastic [CP]	End-of-life vehicles	Transformation of a textile fiber into a secondary material.
18	Blanc et al. (2019)	Micro/Meso (Supply Chain)	Agri/Food [A/F]	Food and Beverage [FB]	Raspberry supply chain	Sustainability of bioplastics in the fruit supply chain.
19	De Meester et al. (2019)	Macro	Capital Equipment [CE]	Electrical and Electronic Equipment [EEE]	Electrical and Electronic Equipment	Environmental performance of the WEEE recycling chain.
20	Buonocore et al. (2019)	Micro	Materials and Fuels [MF]	Wood and Paper [WP]	Wood industry and forestry	Environmental efficiency of bioenergy generation from wood waste.
21	Warrings and Fellner (2020)	Micro/Macro	Materials and Fuels [MF]	Metal and Glass [MG]	Aluminum packaging	Actions to ensure the recycling rates (required by the EU) and the related economic costs.
22	Stanchev et al. (2020)	Micro/Meso (Supply Chain)	Agri/Food [A/F]	Food and Beverage [FB]	Dairy Industry	Environmental performance of anaerobic treatment of milk effluents.
23	Kulczycka et al. (2020)	Meso/Macro	Societal Services [SS]	Waste Management [WM]	Waste from extractive industries	Enhance extractive industry waste statistical data platforms.
24	Kůdela et al. (2020)	Macro	Societal Services [SS]	Waste Management [WM]	Municipal solid waste	Treatment of municipal solid waste.
25	Roithner and Rechberger (2020)	Macro/micro	Societal Services [SS]	Waste Management [WM]	Plastic packaging recycling	Recycling indicator
26	Nika et al. (2020)	Macro	Societal Services [SS]	Water and Sewage [WS]	Water supply	Circularity of water resources.
27	Schmidt et al. (2020)	Macro	Materials and Fuels [MF]	Chemical and Plastic [CP]	PET bottle waste management	Material efficiency indicators.
28	Santander et al. (2020)	Macro	Materials and Fuels [MF]	Chemical and Plastic [CP]	Plastic recycling for 3D printing	Smart network for plastic recycling.
29	Cottafava and Ritzen (2021)	Micro/Meso (Supply Chain)	Construction and Infrastructure [CI]	Construction Materials and Products [CMP]	Residential buildings	Potential recovery of building elements.
30	Ncube et al. (2021)	Micro/Meso (Supply Chain)	Agri/Food [A/F]	Food and Beverage [FB]	Wine Industry	Recovery of by-products of wine processing.
31	Ghafourian et al. (2022)	Micro	Societal Services [SS]	Water and Sewage [WS]	Touristic facilities	Freshwater savings
32	Salminen et al. (2022)	Macro	Societal Services [SS]	Water and Sewage [WS]	Water and water-related ecosystems	A CE perspective for smart water management
33	Abbate et al. (2023)	Micro/Meso (Supply Chain)	Agri/Food [A/F]	Food and Beverage [FB]	Egg industry	Ecological impacts of the egg supply chain.

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Table 1 (*continued*)

N.	References	Implementation level	Economic sectors			Circularity challenges
			Economic Sector Classification	Industry	Specialization	
34	Escribà-Gelonch et al. (2023)	Micro	Agri/Food [A/F]	Food and Beverage [FB]	Fertilizers	A mass circularity indicator (MCI) for agricultural cultivation

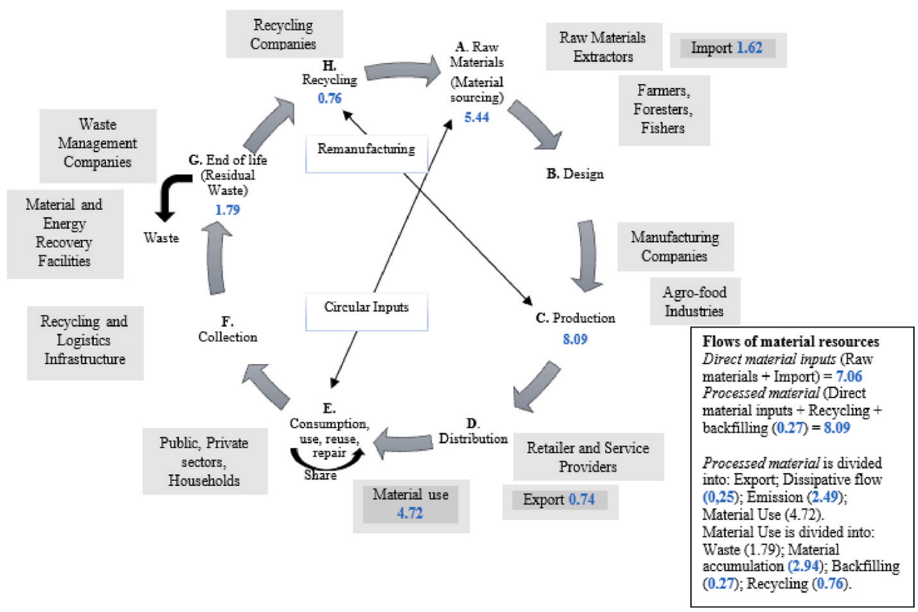

Fig. 4. Resource flows through a value chain in a CE.
Source: adapted from Kalmykova et al. (2018), Accenture Strategy (2014) and Institute for the Environmental Studies (2014) ■ Principal flows of material resources in Gt/year (billion tonnes per year), EU, 2021. Source: Eurostat

= 0.32) in the "Policymakers" category; "Decision-makers" (f_i = 0.24) and "Businesses" (f_i = 0.21) in the "Business" category; instead in the category "Other society stakeholders" emerge "Consumers" (f_i = 0.38) and "Citizens" (f_i = 0.15). These actors are the principal beneficiaries of the economic, environmental, and social benefits associated with CE implementation. Simultaneously, these results demonstrate how a transition towards a circular system can take place from the bottom up when communities, public and private actors decide to switch their way to produce and consume.

5.1.2. *The sustainable capitals and investors' perspective*

Since the CE, according to what established in this study, is mainly an economic model, its implementation relies on the economic feasibility and affordability of circular models compared to linear ones.

Therefore, for each case study, CE initiatives was considered in terms of benefits related to sustainable capital and potentially connected with CE investments.

Table 4 shows that the benefits linked to investment in CE practices cover all economic sectors. The most significant benefits refer to the option of saving (i.e., energy and raw materials) thanks to: the utilization of secondary raw materials; the reduction of dependence on fossil fuels (and the reduction of its environmental impacts); the production of new products with a higher market value than the original by-product; (in some cases) the conservation of soil for agricultural purposes and the reduction of the use of pesticides and fertilizers; but also welfare benefits associated with the reduction of many impact categories (e.g. carcinogenic toxicity for humans, eutrophication, etc.) linked to a linear model. This shows that economic sectors that have adopted an CE model expect this model to be economically viable. Likewise, environmental aspects and consumer awareness imply the pursuit of sustainability as a prerequisite of CE implementation.

5.2. *Obstacles*

To answer the research question "#RQ3. What are the barriers that currently preventing CE implementation in the EU?", the obstacles preventing the full implementation of the CE at EU level are analyzed below.

5.2.1. *Barriers to CE implementation*

To analyze the obstacles in CE implementation, the barriers, deduced from the 34 case studies, were classified based on literature (see: Kirchherr et al., 2018; Grafström and Aasma, 2021). Table 5 shows how some constraints are typical of CE implementation, while others have a meaning only for a particular case study.

Specifically, technological barriers refer to the lack of adequate data, standards or criteria for CE development and measurement. In the context of market barriers, weaknesses emerge in terms of economic instruments such as: taxes, incentives, and subsidies to internalize external costs or for establishing an effective market for secondary products/materials, or in high investment costs. Institutional barriers highlight different political approaches (in domestic and foreign markets). While the cultural or social barriers show the lack of consumers awareness and suggest certifications able to show the benefits of circularity and justifying a possible increase in the market price.

5.3. *Level of CE implementation*

The level of circularity can help to explore which economic sector is developed, in terms of CE actions, compared to other sectors, and provides a starting and useful guide on CE implementation (EMAF, 2015). To assess the level of CE implementation at EU level and to answer the research question "#RQ4. What are the economic sectors that have

Table 2
CE strategies.

Stage of the value chain	Strategies	References														UE Policy
		Kalmykova et al. (2018)	EMAF (2015)	Bocken et al. (2014)	Mestre and Cooper (2017)	Ghisellini, et al. (2016)	Di Maio and Rem (2015)	Masi et al. (2018)	Park and Chertow (2014)	van Weelden et al. (2016)	Li and Su (2012)	Genovese et al. (2017)	Wen and Meng (2015)	Elia et al. (2017)	Scarpellini et al. (2019)	
A. Raw Materials	**A.1** Using compostable/ biodegradable/ renewable materials	X			X											(EC, 2020a; EC, 2005)
	A.2 Reducing non-renewable resources	X	X				X	X	X			X		X		(EC, 2020a; EC, 2005; EC, 2020d; EC, 2020b)
	A.3 Reducing input of materials	X	X					X			X	X	X	X		(EC, 2020a; EC, 2005)
	A.4 Reducing critical materials	X									X	X		X		(EC, 2020a; EC, 2020e; EC, 2020b)
	A.5 Using residual outputs from one process as feedstock for the same or another one	X						X								(EC, 2020a; EC, 2007)
B. Design	**B.1** Reducing the weight and volume of packaging				X											(EC, 2020a); Directive (EU) 2019/904
	B.2 Design and fabricate smart material (Development of new concepts)	X			X	X										(EC, 2020a; EC, 2019a; EC, 2020d)
	B.3 Designing outputs to reduce resource consumption	X				X		X								(EC, 2020a; EC, 2019b)
	B.4 Designing outputs to minimize waste.	X				X		X								(EC, 2020a; EC, 2019b)
	B.5 Design aimed at the reuse/ recovery of materials/ components.	X				X		X								(EC, 2020a); COM (2020) 67; (EC, 2019b)
	B.6 Recyclable Packaging (Designed-to-be-recycled)					X										(EC, 2020a); Directive (EU) 2019/904
	B.7 Products made with sustainable materials	X				X		X								(EC, 2020a; EC, 2019b)

(*continued on next page*)

Table 2 (*continued*)

Stage of the value chain	Strategies	References														UE Policy
		Kalmykova et al. (2018)	EMAF (2015)	Bocken et al. (2014)	Mestre and Cooper (2017)	Ghisellini, et al. (2016)	Di Maio and Rem (2015)	Masi et al. (2018)	Park and Chertow (2014)	van Weelden et al. (2016)	Li and Su (2012)	Genovese et al. (2017)	Wen and Meng (2015)	Elia et al. (2017)	Scarpellini et al. (2019)	
	B.8 Design solutions inspired by durability, repairability, recyclability and disassembly.	X	X			X								X		(EC, 2020a; EC, 2020d; EC, 2019b)
C. Production	**C.1** Provide products/services with reduced energy/resource consumption	X														(EC, 2020a; EC, 2005; EC, 2020d)
	C.2 Tight circle solutions		X													(EC, 2020a; EC, 2019b)
	C.3 Remanufactured Products							X		X						(EC, 2020a; EC, 2005; EC, 2019b)
D. Distribution	**D.1** Use of low environmental impact packaging solutions	X														(EC, 2020a; EC, 2005; EC, 2019b); Directive (EU) 2019/904
	D.2 Reverse logistic					X		X								(EC, 2020a); Directive, 2018/19/EU
E. Consumption, use, reuse, repair	**E.1** Product as a Service	X						X								(EC, 2020a; EC, 2019b)
	E.2 Collaborative Consumption															(EC, 2020a; EC, 2019b)
	E.3 Sharing economy	X														(EC, 2020a; EC, 2020d; EC, 2019b)
	E.4 Sharing Platforms	X														(EC, 2020a; EC, 2020d; EC, 2019b); (EC, 2020b)
	E.5 Maintenance/ repair kit							X								(EC, 2020a; EC, 2019b)
	E.6 Consumption of products (material/ resource) made with recycled elements	X				X									X	(EC, 2020a; EC, 2019b)
	E.7 Use of technology-based application	X														(EC, 2020a; EC, 2020d; EC, 2019b); (EC, 2020b)
	E.8 Reusing product	X														(EC, 2020a; EC, 2019b)

(*continued on next page*)

Table 2 (*continued*)

Stage of the value chain	Strategies	References														UE Policy
		Kalmykova et al. (2018)	EMAF (2015)	Bocken et al. (2014)	Mestre and Cooper (2017)	Ghisellini, et al. (2016)	Di Maio and Rem (2015)	Masi et al. (2018)	Park and Chertow (2014)	van Weelden et al. (2016)	Li and Su (2012)	Genovese et al. (2017)	Wen and Meng (2015)	Elia et al. (2017)	Scarpellini et al. (2019)	
	(material/ resource)															
F. Collection	**F.1** Collection of packaging and product waste (material/ resource) through collective waste recovery systems.	X														(EC, 2020a; EC, 2019b); Directive (EU) 2018/851; Directive (EU) 2019/904
	F.2 Quantitative/ qualitative waste separation	X														(EC, 2020a; EC, 2019b); Directive (EU) 2018/851
G. Residual waste	**G.1** Energy/ materials recovery	X				X										(EC, 2020a; EC, 2019b); Directive (EU) 2018/851
	G.2 Waste valorization	X													X	EC, 2020a; EC, 2019b); Directive (EU) 2018/851
	G.3 Waste reduction					X									X	EC, 2020a; EC, 2019b); Directive (EU) 2018/851
H. Recycling	**H.1** Projects/ actions aimed at the use of recyclable or regenerable waste	X				X										(EC, 2020a; EC, 2019b); Directive (EU) 2018/851
	H.2 Closed-loop recycling	X														(EC, 2020a; EC, 2019b); Directive (EU) 2018/851
	H.3 Partnerships based on sharing (IS)	X		X												(EC, 2020a; EC, 2019b); Directive (EU) 2018/851
	H.4 Open -loop recycling	X														(EC, 2020a; EC, 2019b); Directive (EU) 2018/851

Table 3
Case studies and stakeholder perspective.

Stakeholders' categories	Case studies frequencies (f_i)	References
Policymakers		
Country	0.06	Kůdela et al. (2020); Roithner and Rechberger (2020)
Legislators	0.32	Di Maio and Rem (2015); Huysman et al. (2015); Husgafvel et al. (2016); Daddi et al. (2017); Huysman et al. (2017); Richter et al. (2018); Vanegas et al. (2018); Blanc et al. (2019); De Meester et al. (2019) Buonocore et al. (2019); Schmidt et al. (2020)
Local Authorities	0.06	Hutner et al. (2018); Cervo et al. (2019)
Member States	0.03	Kulczycka et al. (2020)
Municipalities	0.12	Warrings and Fellner (2020); Kůdela et al. (2020); Roithner and Rechberger (2020); Nika et al. (2020);
Public Administrations	0.06	Scarpellini et al. (2019); Santander et al. (2020)
Regions	0.09	Warrings and Fellner (2020); Kůdela et al. (2020); Roithner and Rechberger (2020)
Regulators	0.03	Strazza et al. (2015)
Experts	0.09	Kulczycka et al. (2020); Kůdela et al. (2020); Roithner and Rechberger (2020)
Businesses		
Cluster managers	0.09	Daddi et al. (2017); Cervo et al. (2019); Buonocore et al. (2019)
Businesses (producers)	0.21	Vanegas et al. (2018); Kaddoura et al. (2019); André et al. (2019); Bech et al. (2019); Cervo et al. (2019); Scarpellini et al. (2019); Blanc et al. (2019)
Construction industries	0.06	Jiménez-Rivero and García-Navarro (2017); Cottafava and Ritzen (2021)
Consulting businesses	0.03	Cervo et al. (2019)
Dairy industry	0.03	Stanchev et al. (2020)
Decision-makers	0.24	Husgafvel et al. (2016); Jiménez-Rivero and García-Navarro (2017); Hutner et al. (2018); Kaddoura et al. (2019); André et al. (2019); Bech et al. (2019); Cervo et al. (2019); Santander et al. (2020)
End-of-life vehicles industries	0.03	Gigli et al. (2019)
Energy saving lamp manufacturers	0.03	Richter et al. (2018)
EoL operators	0,03	Vanegas et al. (2018)
Innovative businesses	0.03	Di Maio and Rem (2015)
Mining industry	0.03	Kulczycka et al. (2020)
Plastic recycling SMEs	0.03	Santander et al. (2020)
Primary and end-of-life markets	0.03	Hutner et al. (2018)
Private waste operators	0.03	Schmidt et al. (2020)
Product designers	0.03	Vanegas et al. (2018)
Recycling and Logistics Infrastructure	0.03	Warrings and Fellner (2020)
Recycling industry	0.03	Schmidt et al. (2020)
SMEs	0.03	Daddi et al. (2017)
Technology providers	0.03	De Meester et al. (2019)
Waste industries	0,06	Kůdela et al. (2020); Roithner and Rechberger (2020)
Water supply industry	0.03	Nika et al. (2020)
Wine Industry	0.03	Ncube et al. (2021)
Other society stakeholders		
Academics	0.03	Cervo et al. (2019)
Associations	0.06	Cervo et al. (2019); Gigli et al. (2019)
Citizens	0.15	Husgafvel et al. (2016); Scarpellini et al. (2019); Warrings and Fellner (2020); Kůdela et al. (2020); Roithner and Rechberger (2020)
Consumers	0.38	Daddi et al. (2017); Richter et al. (2018); Vanegas et al. (2018); Kaddoura et al. (2019); André et al. (2019); Bech et al. (2019); Gigli et al. (2019); Cervo et al. (2019); De Meester et al. (2019); Warrings and Fellner (2020); Nika et al. (2020); Schmidt et al. (2020); Ncube et al. (2021)
Local community	0.06	Cervo et al. (2019); Abbate et al. (2023)
Populations of low-density mountain areas	0.03	Buonocore et al. (2019)
Sector Practitioners	0.12	Strazza et al. (2015); Jiménez-Rivero and García-Navarro (2017); Hutner et al. (2018); Cottafava and Ritzen (2021)
Society as a whole	0.03	Di Maio and Rem (2015); Huysman et al. (2015)

contributed most to the CE implementation in the EU?" the following analysis was conducted.

5.3.1. Link between economic sectors and CE strategies

From the 34 case studies (Table 6), it emerges that most of the strategies used in the EU framework are connected to the end of the value chain (42.8% on the overall strategies adopted in the case studies) and mainly involve steps related to recycling (24.2%) and end of life (18.6%). This result is consistent with Ekins (2003) about the investment in natural capital. It means that the most implemented activities are attributable to the "Projects/actions aimed to use of recyclable or regenerable waste (H.1)" (8.8%) and "Waste reduction (G.3)" (7.9%) strategies. The "Reducing input of materials (A.3)" (7.6%) is the most practiced strategy in the "A. Raw Materials" step.

These actions have implications on the conservation of natural capital since they can prevent qualitative degradation, while increasing environmental benefits (Silva et al., 2020; Ekins, 2003).

Similar considerations concern economic capital including the conservation of material value and related to end-of-life strategies (G.1. Energy/materials recovery: 3.1%), all the strategies included in the Recycling step, the use of recycled materials (strategies: "Reducing input of materials (A.3)": 7.6% and "Using residual outputs from one process as feedstock for the same or another production process (A.5)": 4.1%) and to the use of a product in terms of depreciation and durability (strategy "Design solutions inspired by durability, repairability, recyclability and disassembly (B.8)": 2.83%). For social and human capital, the interrelationships developed between economic actors, strategies such as: "Partnerships based on sharing -IS- (H.3)": 3.5% and "Projects/actions aimed at the use of recyclable or regenerable waste (H.1)": 8.8% are considered (Kwok et al., 2019). The presence of these strategies, in many of the case studies, allows to overcome the social and cultural barriers due to the lack of partnership among actors along the value chain. Furthermore, the development of end-of-life activities is consistent with the employment generated in the EU in sectors related to CE implementation.

Regarding the results deriving from this analytic framework, the division by years does not allow significant considerations to evaluate the evolution of CE strategies over time.

However, the best performing industries in terms of circular strategies are Food and Beverage [FB] (17.9%); Chemical and Plastic [CP] (16.4%); Construction Materials and Products [CMP] (11.0%); Water and Sewage [WS] (9.1%); Electrical and Electronic Equipment [EEE]

Table 4
Sustainable development capitals and investors perspective.

Economic (financial and built) Capital	Natural Capital	Social Capital	References
Potential[a]			Strazza et al. (2015)
Benefits related to recycling. New growth opportunities for innovative businesses. Increased revenues. Stimulus to innovation.	Benefits related to recycling.	Benefits related to recycling. Job opportunities.	Di Maio and Rem (2015)
Benefits related to recycling: new products (cascade use) or in the same production cycle (closed loop).	Benefits in terms of resource efficiency.	Job opportunities.	Huysman et al. (2015)
Access to local knowledge. Increase of industrial cooperation. Increased efficiency in the management of regional resources. Optimization of the production process. Greater use of secondary industrial flows as raw materials. Production of fertilizer.	Reduction of environmental impacts. Material recycling. Reduction of raw materials. Reduction in waste production. Increased level of environmental protection.	Potential: thanks to a reduction in environmental burdens which translates into an improvement in human health.	Husgafvel et al. (2016)
Potential	Reduction of non-renewable resources. Resource recycling. Reduction of construction material waste. Recycling of building materials. Landfill emissions prevention. Reduction of GHGs Limited impacts in terms of energy and GHGs.	Potential	Jiménez-Rivero and García-Navarro (2017)
Benefits deriving from the sharing of economic, organizational, and technical resources and from the use of common services and infrastructures. Opportunity to overcome R&D barriers and develop innovative actions.	Reduction of GHGs. Benefits in terms of land use, water, mineral, fossil, and renewable resources. Benefits from the environmental performance of products. Benefits linked to the reuse of wastewater.	Reduction of human toxicity.	Daddi et al. (2017)
Potential: based on the propensity of operators to balance economic performances with environmental ones.			Fregonara et al. (2017)
Recycled plastic waste, based on their quality, allows to optimize both the environmental and the economic benefits.			Huysman et al. (2017)
Potential	Reduction of waste produced. Reduction of environmental impact related to five categories: climate change, water and material depletion, waste production, human toxicity.		Hutner et al. (2018)
Potential cost reduction due to longer product longevity compared to standard products. Reduction of energy consumption thanks to a longer duration and lower energy consumption.	Extending the life of the product leads to a decrease in environmental damage throughout its life cycle.	Potential benefits linked to the trade-off between environmental benefits and costs for consumers.	Richter et al. (2018)
Possibility to improve the efficiency of the recycling of critical metals, valuable metals, and plastics. Possibility to extend the product's durability and increase the recovery rate. Reduction of costs related to disassembly times.	Reduction of environmental impacts related to the extraction, production, and disposal through the recovery of materials from the waste stream.		Vanegas et al. (2018)
Cost reduction. Increased customers' willingness to pay for the environmental performance of products. Supply advantages due to the possibility of dealing with the same supplier.	Reduction of environmental impacts.		Kaddoura et al. (2019)
Potential advantages linked to the increase of metals' functional recycling rates (gold, silver, etc.).	Reduction of environmental impacts related to reuse. Increased functional recycling rates of metals.	Reduction of human toxicity.	André et al. (2019)
Potential			Bech et al. (2019)
Low transport and management costs. Low treatment costs thanks to the internal reuse of some solvent and acid.	Replacement of traditional fuels and raw materials Reuse of calcium carbonate from waste, cardboard, plastic, rubber. Net environmental benefit linked to the quality of the ecosystem, human health, climate change, resources.	Creation of new relationships between independent stakeholders. Benefits for human health.	Cervo et al. (2019)
Long term economic benefits	Benefits deriving from the recycling and waste treatment areas.	Job opportunities (e.g., professional, and specialized jobs).	Scarpellini et al. (2019)
Long-term economic and financial sustainability and profitability. Economic enhancement and savings deriving from the use of by-products.	Reduction of environmental damages coming from the recycling of residual products. Environmental enhancement and savings deriving from the use of by-products.	Potential	Gigli et al. (2019)
Reduction of external costs	Reduction in Global Warming and non-renewable energy. Reduction of pollution.	Benefits related to the reduction of pollution.	Blanc et al. (2019)
Benefits related to the use of secondary materials. Increase and improvement of the recycling chain.	Reduction in the use of raw materials. Improvement of environmental performance and saving of natural resources through an improvement of separation technologies. Benefits related to the use of secondary materials.	Potential	De Meester et al. (2019)

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Table 4 (*continued*)

Economic (financial and built) Capital	Natural Capital	Social Capital	References
Reduction of the demand for fossils. Benefits deriving from the wood bioenergy markets, incentive for multifunctionality in agriculture (especially on peripheral or unused land).	Benefits deriving from the replacement of fossil fuels with woody biomass. Reduction of resource consumption. Reduction of GHGs compared to fossil fuels.	Job opportunities in the bioenergy production chain.	Buonocore et al. (2019)
Potential.	Potential: the recovery plants for municipal solid waste and bottom ash could improve the recycling rate, improvements are also expected from the separate collection system.		Warrings and Fellner (2020)
Biogas production. Fertilizer production. Energy and material recover. Reduction of energy and kerosene consumption.	Limits in the use of raw resources. Recovery of energy and valuable resources. Environmental costs are lower than environmental benefits. Reduction of environmental pressure to water bodies.		Stanchev et al. (2020)
Potential creation of IS.	Reduction of waste.	Reduction of risks associated with waste treatment and increased safety.	Kulczycka et al. (2020)
Potential to tackle local issues (energy supply).	Potential to tackle climate change (mitigation). Energy and materials recovery.	Potential: linked to materials recovery and employment,	Kůdela et al. (2020)
Cost reduction reached by separating high purity materials from waste.	Reduction of environmental costs thanks to the reduction of poorly recyclable materials. Increased recycling targets.	Potential	Roithner and Rechberger (2020)
Efficient use of water resource.	Preservation of water resource. Pollution prevention. Natural capital retrieval.		Nika et al. (2020)
	While the net environmental benefits vary based on the collection and recycling system used, the greater environmental benefits are associated with more efficient recycling cycles.		Schmidt et al. (2020)
Benefits associated with increasing the recycling rate. Benefits deriving from the economic savings achieved from the recycling of plastic waste.	Benefits deriving from a reduction in GHGs and an increase in recycled plastic.		Santander et al. (2020)
Potential	Reduction of environmental impacts at micro, meso, and macro levels.		Cottafava and Ritzen (2021)
Benefits related to the lack of competition between food crops and changes in land use. Benefits linked to the production of bioenergy from wood by-products. Benefits deriving from the transformation of by-products into food products.	Lower environmental impacts deriving from circular production models and recovery of by-products.	Benefits related to the reduction of many impact categories.	Ncube et al. (2021)
Savings in freshwater withdrawal (replaced by treated gray and rainwater). Benefits for agricultural production (irrigation, bio cultivation, production of fertilizers from waste, etc.). Electricity savings	Freshwater savings. Carbon sequestration. Wastewater Treatment. Reduction of mineral extraction. Biodiversity.	School trips/visits Tourism Job creation/retention	Ghafourian et al. (2022)
Reduction of losses of water, energy, and precious raw materials. Increased water efficiency. Brand image	Recycle of treated wastewater. Reduction of water resources stress.	Increased environmental awareness	Salminen et al. (2022)
Local economy development	Reduction of environmental impacts	Benefits linked to a short agri-food chain and related to the revitalization of local communities and the local economy.	Abbate et al. (2023)
Sustainable agricultural practices improve productivity	Environmental advantages related to the use of nanofertilizers (i.e., lower water consumption).		Escribà-Gelonch et al. (2023)

[a] Potential: in the case study there is no explicit reference to the benefits in terms of "Economic Capital (financial and built); Natural Capital; Social Capital" but they could derive from the results obtained.

(6,6%); Waste Management [WM] (5.7%); Fashion and Textiles [FT] (5.0%). The latter aspect is relevant in relation to the key sectors identified by the new CE action plan and involves all implementation levels (micro, meso and macro), with a slight prevalence for the micro level.

Additional information can be obtained through the attribution of a score (%) to evaluate how a specific economic sector adapts to the CE strategies, as expressed in Table 7.

In this perspective, information about both the strategies adopted and the best-performing sectors can be gathered.

As regards the former, it emerges that the strategies that embrace all economic sectors are: "Reducing input of materials (A.3)" relative to the first step of the CE value chain; "Reusing product (material/resouce) (E.8)" in the phase of Consumption, use, reuse, repair; "Quantitative/qualitative differentiation of wastes (F.2)" in the Collection phase; "Waste valorization (G.2)" and "Waste reduction (G.3)" relating to Residual waste; "Projects/actions aimed to use of recyclable or regenerable waste (H.1)" and "Closed-loop recycling (H.2)" in the last stage of the CE value chain (Recycling).

As for the six economic sectors identified from the 34 case studies it emerges that the sectors that record the maximum score (100%) are: Materials and Fuels [MF] with the strategy "Design and fabricate smart material - Development of new concepts- (B.2)" in the Chemical and Plastic industry; Agri-food [A/F] with the strategy "Products made with sustainable materials (B.7)"; Social Services [SS] with the strategies "Reducing the weight and volume of packaging (B.1)" and "Collaborative Consumption (E.2)"; Goods and Services [GS] with the strategy "Maintenance/repair kit (E.5)". The Construction and Infrastructure [CI] sector does not reach the maximum score in any strategy. It also

Table 5
Barriers in CE implementation.

Barriers	References
Technological	
Resource efficiency improvements	Di Maio and Rem(2015)
Necessity to consider the quality of recyclable products	Huysman et al. (2017)
Weak possibility of measuring the effects of waste prevention	Hutner et al. (2018)
Lack of minimum standards	Richter et al. (2018)
Need to refine product durability.	
Need to set specific thresholds for some components (replaceable and repairable components, or those that contain critical raw materials or hazardous substances).	Vanegas et al. (2018)
Difficulties related to the closed-loop recycling strategies primarily due to post-consumer waste	Bech et al. (2019)
Lack of qualified staff	Scarpellini et al. (2019)
Lack of CE standards	
Presence of technical and technological constraints	Gigli et al. (2019)
Need for design changes to improve recycling or dismantling.	De Meester et al. (2019)
Differences in data from different sources	Kulczycka et al. (2020)
Lack of data	Hutner et al. (2018); Kaddoura et al. (2019); Roithner and Rechberger (2020); Schmidt et al. (2020)
Lack of homogeneous and clean (plastic) waste	Santander et al. (2020)
Necessity of detailed guidelines	Cottafava and Ritzen (2021)
Necessity of minimum requirements or standards for practitioners	
Necessity of well-explained design criteria to avoid misapprehensions during the design stage.	
Necessity of a well-documented report of materials and impacts	
Need to implement new technologies and processes	Ncube et al. (2021)
The misunderstanding of the economic costs-benefits of the products and technologies enabling the CE	Ghafourian et al. (2022)
Poor understanding and lack of knowledge and skills	Salminen et al. (2022)
Market	
Possibility of providing subsidies or taxes (e.g., tax refunded) for (plastic) waste management.	Di Maio and Rem (2015)
Lack of resources by SMEs.	Daddi et al. (2017)
Possibility of introducing taxes and/or subsidies to direct waste towards more suitable treatment options.	Huysman et al. (2017)
Lack of incentive systems.	Hutner et al. (2018)
Adoption of different commercial practices across the EU.	Richter et al. (2018)
Financial barriers	Kaddoura et al. (2019)
Economic impracticability (partly overcome by the evaluation of alternative opportunities and market mechanisms)	Cervo et al. (2019)
Lack of investment funds.	Scarpellini et al. (2019)
Difficulty in supplying recycled products.	
Lack of a market oriented towards the recycling of resources.	Gigli et al. (2019)
Need for economic instruments to incentivize the recycling rate, such as government funding or an ad valorem tax.	
High investment costs.	
High production costs	Blanc et al. (2019)
Lack of cost uniformity.	Warrings and Fellner (2020)
Lack of policies to promote recycled plastics through economic instruments.	Santander et al. (2020)
Need for markets for by-products.	Ncube et al. (2021)
Market performing issues and the economic feasibility of smart circular options for water	Salminen et al. (2022)
Institutional (and regulatory)	
Lack of regulation on circular solutions.	Strazza et al. (2015)
Need for policies bale to link economy, society, environment, and well-being.	Di Maio and Rem (2015)
Need to promote regional IS.	Husgafvel et al. (2016)
Need to understand the advantages of recycling in local and regional contexts.	
Institutional context	Kaddoura et al. (2019)
Need for implementation of water quality standards.	Nika et al. (2020)
Limits arising from the non-consideration of the foreign trade of PET waste and recycled PET bottles.	Schmidt et al. (2020)
New economic instruments	Salminen et al. (2022)
Lack of explicit reference to sustainability aspects on product labels and packaging	Abbate et al. (2023)
Social (and cultural)	
Lack of consumers awareness	Hutner et al. (2018)
Possibility to include information on durability of products.	Richter et al. (2018)
Extension of consumer guarantees	
Doubtful company culture	Kaddoura et al. (2019)
Poor involvement in sustainability.	Cervo et al. (2019)
Lack of information transfer processes.	
Lack of collaboration and trust.	
Lack of community sensitivity.	
Difficulty in increasing the utilization of by-products among businesses.	Scarpellini et al. (2019)
Customers do not accept price increases.	
Lack of awareness campaigns on CE.	
Cultural barriers and consumer awareness	Blanc et al. (2019)
Need for CE certifications for justify the higher price of products.	
Lack of the social dimension	Santander et al. (2020)
Failure to involve all the actors of the waste reuse chain and by-products.	Ncube et al. (2021)
Negative opinions or miscommunication with respect to circular solutions	Salminen et al. (2022)

appears that the sector in which the greatest number of strategies activated is "Materials and Fuels [MF]" with a total of 85 strategies (equal to 26.7%), most of which attributable to the Chemical and Plastics Industry [CP] (as highlighted above, section 5.3.1). While the sector with the fewest strategies adopted (25) (equal to 7.9%) is Capital Equipment [CE]. There is also a gap between all economic sectors and the need to quantify the level of circularity based on the CE strategies: strategies such as: "Recyclable Packaging (B.6)", "Tight circle solutions (C.2)", and "Sharing Platforms (E.4)", show a score equal to 0 since none of the case studies adopts the proposed strategies.

It should be specified that if an economic sector shows a score of 100% it means that the strategy has not yet been applied in other sectors, therefore that sector can be considered a "pioneer" in its implementation. Conversely, partial scores allow for the results to be spread across multiple strategies. This occurs, among others, in the case of recycling and valorization of end-of-life waste.

5.4. Analysis of assessment methods in CE implementation and level of circularity

From the 34 cases of study emerge some interesting information also about the assessment methods in CE implementation and level of circularity (Fig. A1 in the Appendix). This allows us to answer the secondary research question, namely: "#RQ5. How is the level of implementation of the EC measured in different EU economic sectors?". The LCA, used in 19 cases, both individually and together with other assessment methods, is the most used methodology to evaluate the circularity, followed by the MFA (5 cases), and by the LCC used for economic assessments. As for the use of indicators, this study does not detect the use of a shared indicator, but each case study uses different indicators to evaluate the CE implementation.

The most used modeling approach is the analysis of case studies or the comparison of scenarios. Accounting is also important, and mainly linked to the use of the MFA methodology.

These results confirm the heterogeneity of methodologies and the lack of a common methods, as evidenced by Vinante et al. (2020); Harris et al. (2021); De Oliveira et al. (2021) and De Pascale et al. (2021).

As regards the level of circularity, interesting results emerge from the comparison between the step "A.Raw materials" (18.9%) with the step "H.Recycling" (24.2%), the good balance of these two steps of the CE value chain brings out the existence, in EU, of virtuous paths that allow to close the cycle.

6. Conclusions

This study, starting from EU policy framework, aimed to evaluate the level of CE implementation in the EU. To this end, through 5 research questions, it investigated which economic sectors, and by means of which strategies, have most contributed to the achievement of the CE objectives, distinguishing between challenges and obstacles. The analysis was conducted through the review of 34 case studies representative from the EU countries.

In this perspective, the challenges were interpreted in terms of benefits for investors and stakeholders, and the obstacles were considered in terms of barriers to the CE implementation. In accordance with the definition of CE used in this paper, it is shown how all aspects related to the creation of value can be applied both to the perspective of stakeholder and investors, this latter through the interpretation of the sustainable capitals (economic, environmental, and social).

The investors perspective made it possible to better understand the dimensions of sustainability (in the shape of sustainable capital) and their link with CE. While the stakeholder perspective has shown that CE actions can produce economic, environmental, and social benefits for all stakeholders.

Furthermore, the use of the CE value chain has allowed to link the strategies, promoted in the 34 case studies, with the different steps of the value chain, allowing to reveal the level of CE implementation in the EU. In this perspective, results found that these strategies reflect more the circulation of waste materials rather than the circulation of by-products, materials, and resources into the CE value chain. However, this research also shown virtuous paths that allow to close the cycle through the balance between the first and last step of the CE value chain, confirming the provisions of the new CE Action Plan, with the "*less waste, more value*" section.

The results highlighted aspects of circularity both for a specific industry and for a specific strategy, allowing for an overview of the level of CE implementation in the EU and a general to be understanding of both performance and gaps.

It appears that the best performing industries (that is the total number of strategies activated on the overall strategies adopted in the EU) are Food and Beverage [FB] (17.9% strategies adopted), under the Agri-food [A/F] economic sector; Chemical and Plastic [CP] (16.3%), under Materials and Fuels [MF] economic sector; Construction Materials and Products [CMP] (11.0%), under Construction and Infrastructure [CI] economic sector. While the economic sector with the fewest strategies adopted (equal to 7.9%) is Capital Equipment [CE].

Conversely, as for the implementation of CE strategies, the sectors that can be considered pioneers in the activation of a specific strategy are Agri-food [A/F], Materials and Fuels [MF] and Social Services [SS], while the less activated strategies (with a score equal to 0) are "Recyclable Packaging (B.6)", "Tight circle solutions (C.2)", and "Sharing Platforms (E.4)".

These result shows how the Chemical and Plastics [CP] industry represents one of the best performing industries in terms of CE strategies adopted. It is consistent with the EU Directive, 2019/904 on single-use plastic products and constitute a relevant aspect also for their massive use during and after the pandemic. This result can also be linked to the Agri-food [A/F] economic sector, which in recent years has recorded an increase in take-away food and the consequent use of disposable packaging. In this perspective, future research could focus more on the usefulness of implementing circular models, which take into consideration the use of food waste as an effective raw material to produce recyclable material (e.g., bioplastics) for use as packaging food or single-use packaging.

However, the analysis showed that some strategies need to be better implemented, i.e., those regarding ecological products or packaging design; or the sharing of underutilized products for reduce both the request for new products and new resources; or the sharing of resources and information through online platforms. The latter can serve as an efficient tool for building local social capital and expanding public involvement.

As regards obstacles, the lack of information on material flows emerged, especially at macro level. In addition, often the statistics and information refer to national data and do not allow a comparison between countries. Likewise, it was found that most CE initiatives are implemented at the micro level and are highly diversified across industries and economic sectors.

Anyway, these results confirms that EU policy instruments on CE can play a central role in promoting the desired transition towards circularity. They also prove how the transition to circularity and the next generation of sustainable, human-centered, and resilient Industry 5.0, in EU economic sectors, cannot happen by itself.

In this regard, European projects could represent a promising and effective opportunity and tool. Indeed, several projects and in different sectors, have been launched in EU to promote CE implementation, for example: the European research project Horizon2020 "FrontSH1P″, which aims to demonstrate how innovative models of circular (bio) economy can act as catalysts for socio-economic growth. It targets four key strategic sectors linked to decarbonizing Europe, namely: wood packaging, food and feed, water, and nutrients, as well as plastics and rubber; the EU Project WIDER UPTAKE which aims to overcome the existing barriers (technological, regulatory, organizational, social, and

Table 6
Link between economic sectors and CE Strategies.

	Case Studies N.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
	Years	2015			2016		2017			2018			2019									2020								2021		2022		2023	
	Economic Sectors	[A/F]	[MF]	[MF]	[MF]	[CI]	[GS]	[CI]	[MF]	[SS]	[GS]	[CE]	[GS]	[GS]	[GS]	[CI]	[SS]	[MF]	[A/F]	[CE]	[MF]	[MF]	[A/F]	[SS]	[SS]	[SS]	[SS]	[MF]	[MF]	[CI]	[A/F]	[SS]	[SS]	[A/F]	[A/F]
	Industries	[FB]	[MG]	[CP]	[WP]	[CMP]	[FT]	[CMP]	[CP]	[WM]	[EA]	[EEE]	[R]	[EA]	[FT]	[CMP]	[EGS]	[CP]	[FB]	[EEE]	[WP]	[MG]	[FB]	[WM]	[WM]	[WM]	[WS]	[CP]	[CP]	[CMP]	[FB]	[WS]	[WS]	[FB]	[FB]
Step of the CE value chain	Strategies																																		
A.Raw Materials (Material Sourcing)	A.1	■			■																■						■				■	■	■	■	
	A.2				■	■	■						■		■				■	■	■									■	■				■
	A.3	■	■	■		■	■		■	■	■	■	■	■	■					■	■	■	■			■	■	■	■		■	■	■		■
	A.4.				■							■		■							■														
	A.5	■	■	■			■	■				■				■		■		■			■				■		■		■				
B.Design	B.1									■																									
	B.2																												■						
	B.3		■				■			■							■		■	■								■				■	■		■
	B.4							■	■						■				■										■			■	■		■
	B.5							■	■			■	■		■					■									■	■		■	■		
	B.6																																	■	
	B.7																		■																
	B.8							■	■	■	■	■	■	■		■														■					
C.Production	C.1		■	■			■				■										■						■	■	■		■	■	■	■	■
	C.2																																		
	C.3											■	■	■	■																				
D.Distribution	D.1									■									■									■						■	
	D.2			■					■			■		■	■		■			■									■						
E.Consumption, use, reuse, repair	E.1												■			■																			
	E.2																■																		
	E.3				■		■							■		■																			
	E.4																																		
	E.5												■																						
	E.6	■			■				■					■							■							■							
	E.7	■								■																						■	■		
	E.8					■	■	■	■	■		■			■												■			■					■
F.Collection	F.1																			■															■
	F.2	■	■	■	■	■	■	■	■			■					■	■	■	■	■	■				■	■	■	■		■	■	■		
G.Residual waste	G.1								■				■							■	■		■		■		■				■	■	■		
	G.2	■	■	■	■	■	■	■	■			■					■	■	■	■	■	■	■		■	■	■		■		■	■	■		■
	G.3	■	■	■	■	■	■	■	■		■							■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■
H.Recycling	H.1	■	■	■	■	■	■	■	■			■	■	■	■	■	■	■		■		■	■			■	■	■	■	■	■	■	■	■	■
	H.2		■	■		■		■	■			■		■	■	■	■			■	■	■	■			■	■	■	■	■	■				
	H.3	■			■	■	■							■		■		■						■	■		■				■				
	H.4	■	■	■	■	■		■	■			■				■		■		■	■		■			■	■			■	■			■	

economic) toward the transition to a CE model for wastewater treatment plants; and so on.

6.1. Theoretical and practical implications

Many theoretical and practical impacts derive from this study regarding CE implementation.

Indeed, several tools have been proposed for this purpose and which could lead to future research on this relevant and rapidly growing topic.

The database of the 34 case studies (Table A1) which can be useful for other types of assessments within the CE implementation theme, i.e., CE levels (micro, meso, and macro), economic sectors and industries, circularity challenges, CE indicators, methods, which may be of interest for CE research on this topic.

The database of CE strategies (Table 2), with 35 strategies suitable to be applied at different stages of the CE value chain. This tool allows the identification of suitable strategies for CE implementation within the value chain. It represents a useful support for companies, policymakers, and the scientific community to investigate, in relation to the different areas of interest and the different steps of the value chain, which strategies allow for alignment with a circular model.

The CE implementation framework at EU level (Table 6), which classifies the case studies according to economic sector and industries. It provides an overview of the adaptation of EU economic sectors to the objectives set by the new Circular Economy Action Plan and EU policy on the subject.

This study also highlights clear implications for cleaner production policymakers. It identifies a portfolio of barriers hampering CE implementation (Table 5) and underlines how policymakers, business and other society stakeholders should be aware of the diversity of options to break down barriers to build momentum for CE implementation at the European level.

Finally, the classification of benefits under the lens of the three dimensions of sustainability (Table 4) offers investors a range of options to initiate circular models and represents a starting point for further theory-building efforts in the field of CE implementation. These efforts should converge the EU towards a circular economic model according to the objectives of the 2030 Agenda for Sustainable Development.

6.2. Future research agenda

Through the lens of the European policy framework, this article provides the picture of CE implementation as a complex, political, and multidimensional process that needs to be studied from many perspectives. The paper presents six main contributions. Firstly, focusing on the CE implementation from the of the stakeholders 'perspective, the research shows how all the actors involved in CE implementation, at different levels and in various capacities, are implementing a paradigm shift in their actions. At the same time, it is highlighted how the transition towards a circular system must take place from the bottom up and is determined by the way in which communities, public and private actors decide to produce and consume.

Evidently, implementing the CE and ensuring its permeability in all economic sectors requires financial investment by business; consequently, this process evolves slowly.

In this perspective, the second contribution lies in the interpretation of the benefits deriving from CE implementation deriving from investments in sustainability.

This was done by applying a triple-bottom-line approach, as the economic-environmental one has been the most used so far. The analysis shows how CE implementation, identified as a major cause of change towards sustainability, plays a significant role in influencing investment decisions, interpreting CE implementation as an opportunity to improve existing models and for the removal of barriers that inhibit growth. In an

Table 7
Evaluation on how each economic sector fits the CE strategies.

Stage of the value chain	Strategies	Economic Sectors (value expressed in % on the overall total of each strategy present in each single case study)					
		[MF]	[CI]	[A/F]	[SS]	[GS]	[CE]
A. Raw Materials (Material Sourcing)	A.1	25	0	38	38	0	0
	A.2	18	18	27	0	27	9
	A.3	29	4	17	21	21	8
	A.4.	50	0	0	0	25	25
	A.5	31	15	23	8	8	15
B.Design	B.1	0	0	0	100	0	0
	B.2	100	0	0	0	0	0
	B.3	20	0	20	40	10	10
	B.4	25	13	25	25	13	0
	B.5	20	20	0	20	20	20
	B.6	0	0	0	0	0	0
	B.7	0	0	100	0	0	0
	B.8	11	33	0	11	33	11
C.Production	C.1	38	0	23	23	15	0
	C.2	0	0	0	0	0	0
	C.3	0	0	0	0	75	25
D.Distribution	D.1	25	0	50	25	0	0
	D.2	38	0	0	13	25	25
E.Consumption, use, reuse, repair	E.1	0	50	0	0	50	0
	E.2	0	0	0	100	0	0
	E.3	25	25	0	0	50	0
	E.4	0	0	0	0	0	0
	E.5	0	0	0	0	100	0
	E.6	67	0	17	0	17	0
	E.7	0	0	25	75	0	0
	E.8	10	30	10	20	20	10
F.Collection	F.1	0	0	50	0	0	50
	F.2	41	9	14	23	5	9
G.Residual waste	G.1	20	0	20	40	10	10
	G.2	33	8	21	25	4	8
	G.3	36	12	24	16	8	4
H.Recycling	H.1	29	14	18	18	14	7
	H.2	35	20	10	15	10	10
	H.3	18	18	18	27	18	0
	H.4	33	22	22	11	0	11

ever-increasing and sometimes mandatory regulatory environment, this result is of great importance and deserves further investigation.

The third contribution lies in the identification of the barriers hindering, at EU level, the implementation of CE, indicating technological, market, institutional, cultural, and social issues as the main obstacles to the transition process, and highlighting governmental problems, economics, knowledge, skills, and management issues, as well as the structure of the CE itself.

As regards the fourth contribution, this research, inspired by the identification of which economic sectors, in the EU, are more circular, adopts both a time horizon and a focus on individual economic sectors and CE strategies, and opens to a "broader perspective" on the CE implementation. This perspective allows for comparisons between organizations, sectors and strategies experimenting with CE practices, and how different economic sectors respond to this paradigm shift.

While as regards the level of circularity, the comparison between the "A. Raw materials" step with the "H. Recycling" step, within the CE value chain reveals the existence of virtuous paths, in the EU, that allow the cycle to be closed. Finally, regarding the measurement of CE implementation, this analysis confirms the heterogeneity of methodologies and the lack of common methods.

However, open questions remain, outlining some avenues for future research. We particularly recommend testing the CE strategy framework and key considerations regarding CE implementation in industries and economic sectors, illustrated in this study, through case studies derived from sources other than the academic literature or by proposing other aggregations; including different methodologies both to test our findings and to clarify contexts in which they might not apply.

We have also observed a shift to CE adoption in the Food and Beverage industry. The practical consequences of this change provide a whole range of new lines of research and the potential of this transition for a CE implementation in the whole corresponding economic sector (Agri-food) could be investigated empirically. For the affirmation of a circular business model, we recommend working for a stronger integration of the CE value chain, but also on the integration between the Food and Beverage and the Chemical and Plastics industries, to arrive at alternative solutions that allow to boast the use of strategies such as: "Recyclable Packaging" or "Tight circle solutions".

Furthermore, future research could focus on a specific CE level, or a category of stakeholders, or a single dimension of sustainable capital, with the aim of better understanding the policy and practical aspects of CE implementations and how these will continue to develop in the future.

6.3. *Limitations*

While every effort was made to include as much literature on the topic as possible, this study focuses only on scientific articles. This evidently entails limits due to the exclusion of i.e., of proceedings, practitioners' literature, technical reports. As a result, there may be a gap between what is covered by the academic literature and the actual level of CE implementation.

Conversely, all research articles based on case studies from the EU, even if published by authors affiliated with countries other than the EU, were considered in this review.

Secondly, the review was limited to the use of the keyword "circular economy" present in the title, in the keywords or in the abstract of the selected papers, following the methodological approach used in the literature to conduct reviews on this topic. Consequently, documents that used similar terms (e.g., circularity, closed-loop economy, industrial symbiosis, etc.) or that did not contain the keyword "case study" or "assessment" were probably excluded.

Furthermore, the process of collecting records and classifying the case studies may have been influenced by a certain level of subjectivity. This subjectivity could concern i.e., the choice of records to be included in the screening process (which had to respond to the inclusion/exclusion criteria); the attribution of the selected case studies to a specific CE level (micro, meso, macro); the classification of the case studies in relation to the different steps of the CE value chain and the relative construction of the evaluation framework.

However, these limits are common to most of the research on this topic and derive from the lack of an unambiguous definition of CE. The future research agenda may address these limitations.

Author contributions statement

All the authors: investigation; methodology; writing; validation – original draft; writing, review & editing; A. De Pascale: conceptualization; C. Giannetto; M. Limosani: Validation; G.Ioppolo; K. Szopik-Depczyńska; M. Lanfranchi: supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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