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Doctoral Thesis

Assessing Circularity and Sustainability in Agri-food companies

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Summary

Abstract

The circular economy paradigm of production and consumption, which aims to overcome the end-of-life concept by proposing closed loops of inputs and resources, is now gaining momentum as a possible way to address sustainable development. The environmental, economic, and social challenges of the agri-food sector make it critical for attaining sustainability.

In this context, the present thesis aims to provide a guide for companies of the sector for assessing and reporting circularity, considering the specific features of the sector.

To achieve this aim, the thesis is articulated in i) the state of the art regarding circularity implementation at micro and meso levels in the sector ii) an empirical analysis of circular economy drivers and barriers to implementation and assessment among a selected sample of Portuguese companies of the Agri-food sector; and iii) a preliminary case study analysis on Circularity and environmental sustainability assessment at the company level. The final chapter presents a preliminary theoretical framework able to guide companies towards the assessment and reporting of circular strategies in line with the environmental, economic, and social declination of sustainability and specifically targeted for the needs of the companies of the agri-food sector. Overall, the various chapters provide numerous insights into Circularity implementation and assessment at the company level in the sector. In general, the findings of the present thesis demonstrate that companies' interest in circularity implementation is increasing in the sector. Moreover, circularity principles are already embodied in the food roots, being often related to conventional productive techniques. The thesis, by designing the framework, concludes with theoretical considerations on how to support the sector towards the assessment of their practices to avoid potential burden-shifting or green-washing. Despite the framework having been validated by some companies of the sector already adopting circularity, it needs to be tested in a case study. Finally, the thesis is a first attempt to foster the assessment and reporting of circularity in the agri-food sector. Moreover, the thesis provides insights for future research to achieve a transparent transition to the Circular Economy in particular in the Agri-food sector.

Keywords: Circular Economy; Sustainability; Agri-food; Assessment

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List of abbreviations

- (AD) Anaerobic digestion
- (AD-CHP) Anaerobic digestion and combined heat power generation plant
- (AFS) Agri-food sector
- (AP) Acidification potential
- (CAP) Common Agricultural Policy
- (CE) Circular economy
- (CED) Cumulative Energy Demand
- (CHP) Combined heat and power
- (CSRD) Corporate Sustainability Reporting Directive
- (DNSH) Do Not Significant Harm
- (EMF) Ellen McArthur Foundation
- (EP) Eutrophication potential
- (ESRS) European Sustainability Reporting Standards
- (EU) Europe
- (FU) Functional unit
- (GIFT) Green Investment Financial Tool
- (GWP) Global Warming Potential
- (HT) Human toxicity
- (ISO) International Standardization Organization
- (KPI) Key performance indicator
- (LCA) Life Cycle assessment
- (LCC) Life Cycle costing
- (LCSA) Life Cycle Sustainability Assessment
- (MAE) Marine Aquatic Ecotoxicity
- (MCDA) Multi-criteria decision analysis
- (MCI) Material Circularity Indicator
- (ODP) Ozone layer depletion potential
- (PEFCRs) Product Environmental Footprint Category Rules
- (POFP) Photochemical oxidation potential
- (SD) Sustainable development

- (SDGs) Sustainable Development Goals
- (SFDR) Sustainable Finance Disclosure Regulation
- (S-LCA) Social Life Cycle assessment
- (UNI) Italian National Standard Body
- (WOS) Web of Science

Chapter 1 Introduction

"Few things are as interwoven with human existence and culture as food"
(Ellen Mc Arthur Foundation, page 8 2019).

1.1 Circularity in the Agri-food sector: Challenges and call for action

The agri-food sector (AFS) has a central role in the worldwide productive context since it relates to obtaining and distributing the primary source of livelihood. The AFS is articulated, covering "the journey of food from farm to table including when it is grown, harvested, processed, packaged, transported, distributed, traded, bought, prepared, eaten, and disposed of. It also encompasses non-food products that also constitute livelihoods and all the people as well as the activities, investments and choices that play a part in getting us this food and agricultural products" (FAO, 2021, page 3).

The sector has traditionally followed the linear paradigm for production and consumption, where materials get collected, turned into products, and ultimately thrown away after use (De Bernardi et al., 2023): a paradigm that many experts consider unsustainable (Abbate et al., 2023).

Currently, the biggest concern regards providing equal and affordable access to food to an increasing global population, which will reach 9.5 billion by 2050 (Abbate et al., 2023). Unfortunately, this puts extreme pressure on the environment and society (Fassio and Chirilli, 2023). For example, the agricultural context heavily depends on mineral fertilizers and pesticides, which release toxic substances in water, air and land (Abbate et al., 2023). Thus, the food system plays a significant role in climate change due to its relevant contribution to greenhouse gas emissions and freshwater consumption (Ghisellini et al., 2023). Despite the efforts to meet the food demand, the sector is very wasteful; it is responsible for 700 million tons of waste in Europe every year, putting negative pressure on the environment and compromising biodiversity (Fortunati, Morea, and Mosconi, 2020). Food loss and waste are primary concerns for AFS that affect developing and developed countries. In developing countries, the loss occurs mainly in the post-harvest phase, while in developed ones in the distribution and consumption (Hamam et al. 2021). Overall, part of the population is highly wasteful, while the other deals with food insecurity (Ciccullo et al., 2020).

The external shock of COVID-19 has further challenged the situation; FAO projections estimate that 670 million people will face undernourishment in 2030, 78 million more due to the pandemic (FAO 2022). The different impacts and rates of recovery coupled with limited social protection have worsened the preexisting inequalities, hampering the path to the zero-hunger target set by the UN 2030 Agenda. Recently, the war in Ukraine has been causing grain, fertiliser, and energy shortages, contributing to the risk of exacerbating such inequalities (FAO, IFAD, UNICEF, WFP and WHO, 2022.).

In this context, the AFS has a strategic role in achieving many of the Sustainable Development Goals (SDGs) set by the United Nations for the Agenda 2030. Although related with all SGD, AFS directly addresses SDG 1 (No Poverty), SDG 2 (Zero Hunger) and SDG 3 (Good Health and Well-being) by affecting agricultural productivity, rural livelihoods, food security and correct nutrition (FAO, 2023). The urgency to redirect the AFS towards an environmentally, economically, and socially sustainable path has brought attention to the circular economy (CE).

At the European level, the criticality of the sector in the transition to CE has been noted since the 2015 Action Plan, which had seen food waste as a primary area of intervention (European Commission, 2015). In 2020, it was directly addressed in the European Green Deal plan through the Farm to Fork initiative that put the development of a fair, healthy and sustainable food system as a primary objective for the transition (Ghisellini et al., 2023). In the same direction moves the Common Agricultural Policy (CAP), which reaffirmed for the period 2023-27 the importance of contributing to the goals defined by the Green Deal and committing to the needs of the agricultural sector in terms of equity and fairness, e.g., through better income support, for a 'greener and fairer CAP' (European Commission, 2023).

CE proposes a model in which resource use and waste are reduced by narrowing, slowing, or closing the circulation of materials and energy (Brandstrom and Saidani, 2022). There are different definitions of CE, among the non-academic ones, the Ellen McArthur Foundation (EMF) defines CE as “A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (EMF, page 7, 2013). Whether, among the widespread definitions in scientific literature, the one provided by Kirchherr et al. page229 (2017) defines CE as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers".

CE principles are often associated with the R framework, which describes strategies all beginning with the letter "R" that can range from 3 to 10 Rs (Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover) (Luthin et al., 2023).

The AFS is already familiar with circularity principles. The agricultural sector used to align to natural cycles; crops, dairy or forestry byproducts were considered inputs for other food cycles. The rise of industrial agriculture led the sector to fall far from natural cycles, favouring products out of the food system (Ghisellini et al., 2023). Several authors stressed the pre-existent relation with circularity in the agricultural context. For e.g., Barros et al. (2020) identified as a typical example of closing the loop the use of animal sewage and waste as crop fertilizer.

Introducing circularity into business models can guide companies towards economically viable strategies to reduce environmental impacts, ensuring their long-term resilience in the market (Brandstrom and Saidani, 2022). Thus, the capacity to implement and communicate the CE strategies adopted to the different stakeholders has become a priority for companies (Valls-Val et al., 2022).

Adopting CE is even more challenging in the AFS, where the complexity of the supply chain makes it difficult to identify the sources that contribute to circularity and to define how CE can generate value (Poponi et al., 2023). Indeed, there are still several barriers to CE implementation in the sector. Specifically, some authors evidenced the lack of a common assessment as a hampering factor for CE adoption (Roos Lindgreen et al., 2022; Saidani et al., 2019; Kristensen & Alberg Mosgaard, 2020). Defining CE monitoring indicators was evidenced as a key step in guiding companies towards circularity by the EU (COM 102, 2020). Companies need clear indicators to easily communicate the value of the circular strategies implemented (Valls-Val et al., 2022). Such attention led to the nominee of an ISO Technical Committee (TC323) for developing guidelines and monitoring tools to guide CE implementation at the company level (ISO, 2023).

Several circularity indicators were analysed in the literature (Roos Lindgreen et al., 2021; Brandstrom and Saidani, 2022; Rigamonti and Mancini 2021). However, some criticalities persist. Circular indicators are usually focused on single dimensions of analysis, missing the holistic nature of CE (Rigamonti and Mancini, 2021). An even more crucial aspect is their connection with environmental sustainability. Indicators tend to concentrate on material efficiency, sometimes neglecting energy use, which effectively narrows the scope of the assessment. This limited angle of analysis may lead to significant burden-shifting or cause rebound effects in other parts of the supply chain (Brandstrom and Saidani, 2022). The abundance of indicators, overlapping to some extent, makes the CE assessment complex and still inadequate for companies (Luthin et al., 2023). Such complexity may generate greenwashing behaviours since companies select only those indicators that give positive feedback to their choices (Opferkuch et al., 2023). Furthermore, companies need a balance between the economic sustainability of their business, namely a positive cost-benefit opportunity and the environmental, economic, and social issues arising from their activity (Silvestri et al., 2022).

However, the debate on CE assessment is at the initial stage, especially for the AFS (Poponi et al., 2022a). The food system indeed, deals with features (e.g., perishability) that require a different approach than the non-biological sector (Van Schoubroeck, Vermeyen, and Alaerts, 2022). Another key point is to assess both circularity and environmental sustainability since being circular does not imply being environmentally sustainable and vice versa. However, there is still a limited number of indicators suitable for the AFS. Roos Lindgreen et al. (2021), in testing several circularity indicators for anaerobic digestion and bioconversion of food waste highlighted the lack of indicators able to capture recycling activities within biological cycles.

Thus, given the importance of the AFS in the transition to CE and the current lack of a common assessment method for CE that addresses all the sustainability pillars, the present thesis aims to define an assessment framework able to guide companies towards the implementation and assessment of circular strategies, in line with the environmental, economic, and social holist dimensions of sustainability and specifically targeted for the need of the AFS.

The upcoming sections in this chapter delve deeper into the research gaps, offering a more detailed exploration of the challenges and opportunities identified in implementing and assessing Circular Economy strategies at the company level within the agri-food sector.

1.2 Research questions, methodological approach and scientific structure of the thesis

This sub-section outlines the social research methods utilized to fulfil the research objectives, encompassing the methodological choices made throughout the entirety of the research project, according to the Research Onion model proposed by Saunders et al. (2012). The thesis adheres to an interpretive research philosophy, aiming to conduct comprehensive analyses of phenomena while acknowledging the subjective interpretations of the researcher to gain deeper insight into the subject matter. Consistent with this approach, an inductive research approach (Saunders et al., 2012) was adopted, facilitating the collection and analysis of how previous studies had contextualized CE strategies in the AFS. Survey and archival research served as the primary research strategies employed at different stages of this research. The overall thesis employed various data collection methods, including literature review, content analysis, interviews, semi-quantitative surveys, and focus groups (further elaborated in subsequent subsections). A mixed-methods approach underpinned by both qualitative and quantitative data techniques was adopted, in line with the principles outlined by Bryman et al. (2021). Moreover, a cross-sectional research design allowed us to generate a truthful picture of the current implementation of CE in companies of the AFS. On a geographical scope, the study presented in Chapter 2 analyses CE practices described in the scientific literature at a global scale. Following this, the geographical context was narrowed to EU, focusing on companies operating in Portugal and Italy, with different analysis methods. This choice in terms of context was due to EU progress in the two main topics of this thesis, 1) the CE action plan and 2) The farm to fork initiative, part of the Green Deal. Therefore, empirical evidence was produced using primary data from companies operating in Portugal (Chapter 3) and Italy (Chapter 4). Furthermore, the thesis adopts an interdisciplinary approach, meant is the combination of knowledge and skills from different disciplines to address a given problem (Menken & Keestra, 2016). Indeed, CE integrates per se economic activities with environmental and social well-being (Murray et al., 2017). Specifically, CE has been explored in the AFS context from the perspective of sustainable development, CE literature, and related management fields.

The thesis adopts a hybrid structure, blending article collection with monographic paragraphs; the overall structure is described in figure 1. The figure illustrates the primary research gaps addressed, the underlying hypotheses, methods of validation, and the thesis contribution on the advancement of the topics analysed. The three identified research gaps lead to three different research areas within the thesis. These areas and their outcomes are presented in the following subsections:

- Section 1.3 State of the art of CE implementation in the Agri-food context (Chapter 2 – Paper 1),
- Section 1.4 CE assessment and implementation in the agri-food sector (Chapter 3 – Paper 2),
- Section 1.5 Assessing circularity and sustainability in the agri-food sector (Chapters 4 and 5 – Paper 3).

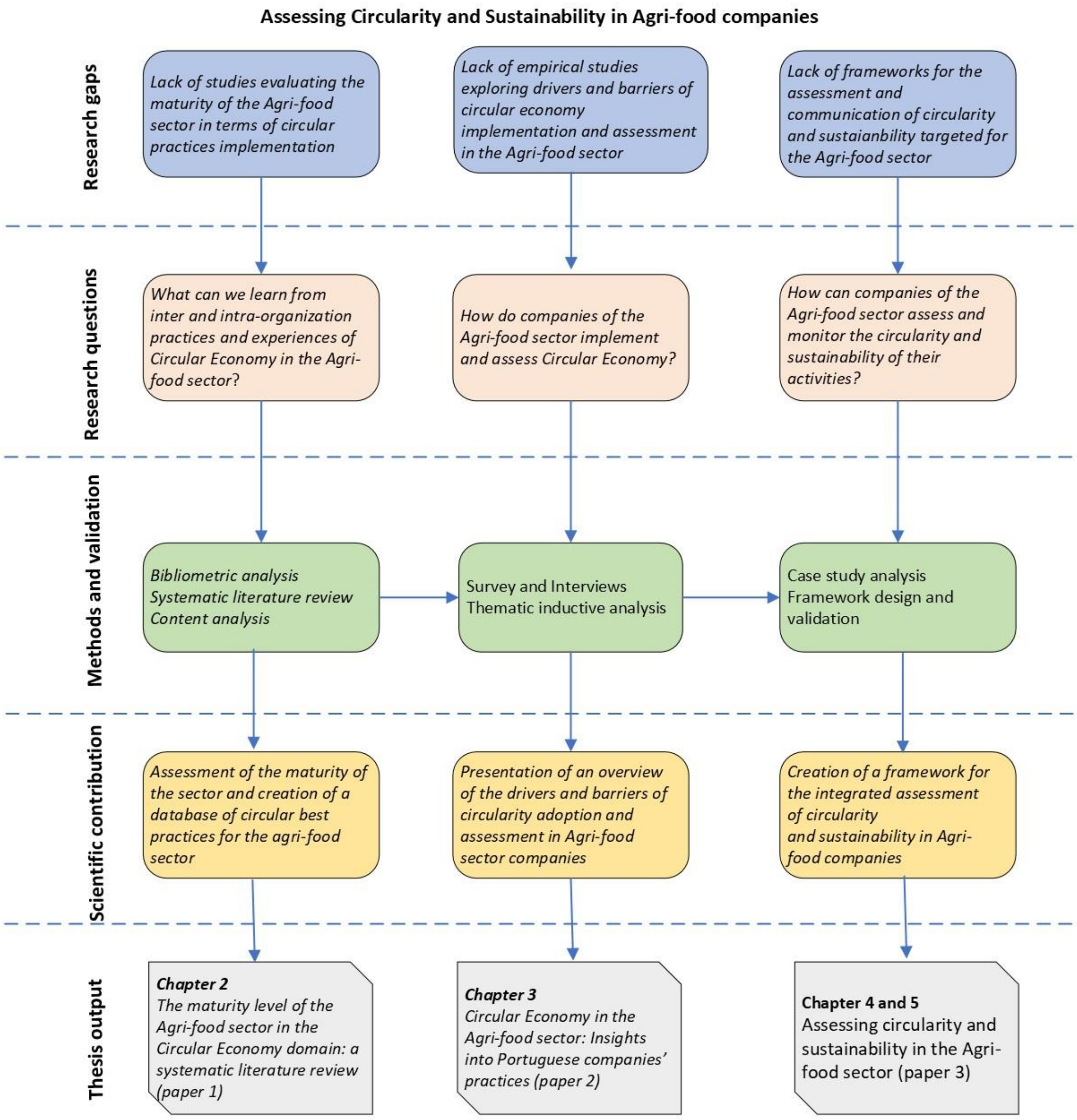

Figure 1 Scientific structure of the thesis

1.3 State of the art of Circular Economy implementation in the Agri-food context (Chapter 2 – Paper 1)

1.3.1 Research gaps and hypothesis

The study of CE in the agri-food context is widespread in literature; in the last years, several authors addressed its application (Esposito et al., 2020; Hamam et al., 2021; Chiaraluce et al., 2021; Barros et al.2020).

Despite this, previous efforts in literature have focused little on individual circularity practices. For this reason, studies focused on case study analysis would be necessary to consider circularity studies and practices, in their natural context, encouraging their in-depth analysis (Crowe et al., 2011).

Among the challenges in the industry, should be included proposing a waste management system that can optimize the residual value of individual streams to turn streams into resources. Some classification systems are already in place, one of the best known being provided by waste hierarchy (European Commission, 2008), but others are proposed in the literature (Papargyropoulou et al., 2014; Garcia-Garcia et al., 2017; Rood et al., 2017). However, a common system identifying the underlying processes and objectives of industry practices to link them to the R framework is still lacking. This would provide more clarity on how to valorize by-products or waste streams according to a system of increasing circularity.

The presence of circularity principles in the sector before the very definition of CE has been repeatedly discussed in the literature. Examples of how to close the cycle of resources and waste are given in animal husbandry (Barros et al., 2020), wheat cultivation (Dossa et al., 2022), but also as basic principles in farming communities (Fassio and Tacco, 2019). Despite the examples, no scientific contribution has ever analyzed circularity practices from this perspective, revealing a significant gap in literature.

To fully capture the circularity outcomes at the company level it is necessary to investigate both intra and inter-firm dynamics. CE indeed fosters connections and collaborations among companies, generating collaborative networks with companies of the same or different sector or size (Kanda et al 2021). In doing so, CE meets Industrial Symbiosis (IS) since companies gather a competitive advantage through the exchange of resources and services (Chertow, 2000). At the same time, CE and IS may be valuable approaches to sustainable development (SD). Nevertheless, CE does not imply sustainability, since burden shifting may arise between different stages of the supply chain (Korhonen et al., 2018). Thus, the relationship between CE and sustainability is unclear but needs to be clarified. A theoretical overview conducted to contextualize CE presence in the agri-food context highlighted the presence of many contributions on the topic, however no study has explored the maturity of the sector in terms of circularity.

For these reasons, the present research proposes a bibliometric and systematic literature review addressing the research question:

RQ1 What can we learn from inter- and intra-organization practices and experiences of CE in the Agri-food sector to assess the circular maturity of the sector?

1.3.2 Methods and validation

To explore the state-of-the-art of available CE implementation in the AFS two methods were adopted: a bibliometric analysis and a systematic literature review enriched by a content analysis. The analysis aims to comprehend circularity practice's characteristics in the AFS, proposing a classification of such practices per process and specific goal and evidencing their innovative or traditional nature to capture the maturity of the sector. Moreover, by adopting a content analysis, it aims to explore the possible connection between CE and IS and if and how they may contribute to redirecting the sector towards SD.

1.4 Bibliometric analysis

Bibliometric analysis allows exploring texts by evaluating information regarding authorship, affiliation, and keywords, also considering the linkages between and among studies (Geissdoerfer et al. 2017). It can be used to map scientific knowledge and evaluate the evolutionary nuances of a specific field, analysing unstructured data systematically and rigorously (Donthu et al., 2021).

The category includes bibliometric information regarding the title of the contribution and authors, the year of publication, the journal source, as well as the subject area covered. This information allows for detecting the annual rate of publication on the field, emphasizing possible trends or discontinuities in the time laps evaluated. The analysis of the journals enables us to identify the sources that contribute the most to the topic, explore the research areas of the journal, to understand the spectrum of subjects dealing with circularity in the agri-food context.

1.4.1 Systematic literature review

To support and explore the bibliometric analysis findings, a systematic literature review was performed (Grant & Booth, 2009; Snyder, 2019). Once the research question, a systematic review allows to summarize the study findings in a transparent and reproducible way, minimizing possible bias (Snyder et al. 2019).

Despite some reviews being published on CE implementation in the food context, none of them focused on case study analysis, exploring the maturity of the sector and considering both the intra and inter-company relations and practices. The definition of the present research question and the CE features to attention were indeed based on a critical reflection regarding the previous studies conducted in the literature on the topic. To ensure the reliability of the revision procedure together with the replicability of the analysis, the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) method was adopted as a guideline for the present review (Page et al., 2021). The databases Scopus and Web of Science (WOS) are selected to guarantee the inclusion of high-level quality articles, which is relevant to examine the state of the art on the research topic. The research interval goes from 2015 to February 2022. 2015 was selected as the starting period of analysis for the launch of "Closing the Loop: An EU Action Plan for the Circular Economy Package" by the European Commission (EC, 2015). Articles were screened first using database exclusion criteria and then using secondary exclusion criteria, namely title, abstract and keywords. The remaining articles were then downloaded for the full-text evaluation. Eligibility criteria, according to the scope of the analysis are selected, i.e., articles presenting case studies (e.g., reviews were excluded), describing practices linked or attributable to CE, linked to the agri-food sector, having a micro or meso level of analysis.

To synthesize the research evidence, the contributions of the sample are analysed and classified into 4 macro-categories of results: i) Bibliometric information, ii) Context of the studies, iii) Agri-food practices description and classification and iv) Sustainable narratives. The last category aimed at exploring the possible connections between CE industrial symbiosis, and sustainable development; such information was gathered and analysed through content analysis technique. This technique enables an interpretation of texts based on a systemized coding process. It explores the current practices and targets, identifying relevant patterns and themes (Moldavska and Welo, 2017).

The information collected from these categories was analysed to discover underlying patterns and critically analyse the features of CE adoption in the food context at the company level.

1.4.2 Scientific contribution and thesis outputs

The present chapter is expected to assess the level of maturity of the AFS through the analysis of circular practices described in scientific literature. Moreover, the analysis will contribute to understanding the relationship between CE and other sustainability-related narratives, analysing if and how the agri-food studies selected present circularity as singular or as related to other SD narratives, like industrial symbiosis, through content analysis. The final aim is to create a solid database of circular best practices for the sector, which can be a reference for companies in the sector to further implement circularity within their operations. Despite CE gaining considerable interest, the path to its full implementation is still long and companies need guidance to implement circularity effectively.

1.5 Circular Economy assessment and implementation in the agri-food sector (Chapter 3 – Paper 2)

1.5.1 Research gaps and hypothesis

CE may be a valuable tool in the AFS to reduce environmental impacts associated with companies' activities, promote employment, and decrease their operating costs (Martins, 2020). However, CE assessment is still poorly implemented at micro level of analysis (Moreno et al., 2021) and companies struggle to implement circularity into their business strategies (Roos Lindgreen et al., 2022). To capture such hampering factors, empirical studies for the characterization of CE in the sector are needed. Including directly agri-food companies' perspectives is essential to limit the gap between academic models and companies' reality (Silvestri et al., 2022). The limited adoption may be related at the company level to poor assessment tools for CE in the sector (Poponi et al., 2022), limiting companies' capacity to monitor the progress made and share the value created with their stakeholders. CE is still considered mainly in environmental terms (Geissdoerfer et al., 2017), overlooking the potential social and financial benefits it may produce, making it a competitive advantage for companies and communities in the long term. Poponi et al. (2022), emphasized the social value generated by CE e.g., fostering sustainability practices along the supply chain and the close community.

In this context, several European policy interventions mentioned circularity as a goal. Recently, the EU Taxonomy Regulation (European Parliament and Council, 2020), to define and support sustainable investments, and the CSRD, which will enlarge the type of companies subjected to sustainability reporting(European Parliament and Council, 2022), following the guidelines provided by EFRAG, which include CE and resource use strategies (ESRS-5), (EFRAG, 2022), to align the Green Deal goals with the Platform for Sustainable Finance. Also, the Italian National Institute of Unification (UNI) is moving in this direction with the UNI/TS 11820, which identifies a set of indicators that enable companies and organisations to assess, measure and manage their circularity (UNI/TS 11820:2022).
This highlights how companies will increasingly have to include circularity in their decisions, learning to quantify and communicate the value of the strategies implemented. Thus, it is relevant to identify suitable methodologies for the valorisation and reporting of the financial impacts associated with CE. Recent literature analyzed the impact of CE on companies' financial performance (Gonçalves et al., 2022; Mazzucchelli, et al., 2022). However, the agri-food context, where the lack of financial resources is perceived as a significant barrier to CE, is still underexplored (Mehmood et al., 2021; Farooque et al., 2019). To explore the mentioned gaps, it is relevant to focus on companies' experiences and perspective by conducting empirical analysis. Given the interest and the initiatives shown for the promotion of circularity (e.g., CE Action plan), the European context was chosen. Then, Portugal was selected as system of analysis. First, due to the centrality of the AFS in the national economy; specifically, food and beverage trade and serving accounted for more than one fifth of the total number of persons employed in non-financial services sector in 2019, but Portugal also recorded 16.2% of value added for food and beverage trade and serving within non-financial in 2021 (Eurostat, 2022). Second, it has promoted several projects to encourage the transition of the sector, such as National Strategy to Combat Food Waste (ENCDA) that promotes the concept of shared responsibility of producers and consumers, or the National Strategy for Organic Agriculture and a Plan of Action to promote the production of organic food products (ENAB) (EEA, 2022).value added, the highest share of F&B trade and serving within non-financial services was recorded in Portugal (16.2 %),

In addition, the PhD scholarship linked to this thesis included a six-month secondment abroad, for which Portugal was chosen. During the secondment to Universidade Aberta (Lisbon), the support of the GreenUPorto research centre made it possible to identify a relevant sample of companies already adopting CE to collaborate with.

Given the identified gaps in the literature on CE assessment, CE social value benefits and financial impact, these topics are the object of the present study, which will answer the main research question:

RSQ2: How do companies of the AFS implement and assess CE?

1.5.2 Methods and validation

To explore how companies of the AFS implement and assess circularity, a mixed research approach was adopted. The final aim was to identify companies of the AFS already implementing CE to interview; to do so, first networks of companies familiar with sustainability and circularity related topics were identified. To define a valuable sample of companies in the Portuguese food context, a purposive sampling technique was adopted; the aim was to select respondents in line with the goal of the study encouraging an in-depth analysis (Campbell et al., 2020). Thus, the sample is not representative of the whole target population, including only companies in line with the study goal (Saunder et al., 2012). To check their actual implementation of circular principles, a survey was designed and administered to a convenient sample of companies involved in sustainability-related networks (n=148). Of the 31 responding companies, 28 declared to adopt circularity principles in their businesses, although only 16 companies described actual circular practices. Of the remaining 16 companies, 9 were available to be interviewed. Thus, the final sample was made of 9 companies.

Moreover, the survey findings were used to design the interview guidelines. The interview guide was articulated into open-ended questions considering CE drivers and barriers of adoption, CE assessment in terms of benefits and obstacles as well as monitoring tools, CE social value creation and adoption in companies initiatives, and CE impact on companies' financial performance, examining tools and barriers. The interviews were explored via inductive thematic analysis (Braun & Clarke, 2006). Inductive coding allows us to determine themes based on the data collected and for this reason, is considered suitable for exploring novel research areas; inductive coding is used in new research areas, like in the present study (Joffe and Yardley, 2003). All the interview information was imported into the qualitative data analysis software, QSR NVivo 1.4 (QSR International, 2021).

1.5.3 Scientific contribution and thesis outputs

This chapter aims to provide a snapshot of the implementation and evaluation of CE in a sample of AFS companies in the European context. The survey will allow identifying companies already implementing circularity to interview. Therefore, the study will deepen the identification of the perceived benefits and barriers of the selected companies in adopting and evaluating circular strategies. Furthermore, the analysis will contribute to understanding whether companies perceive the relationship with the social pillar of sustainability and which social initiatives they adopt to pursue circularity. Finally, it will help characterise the impact of circularity on the financial performance of companies, understand how companies measure this aspect of circularity, and highlight the main obstacles to financial measurement.

1.6 Assessing circularity and sustainability in the agri-food sector (Chapters 4 and 5 – Paper 3)

1.6.1 Research gaps and hypothesis

Assessment of CE remains limited, posing a potential obstacle to defining and implementing efficient CE strategies (Coluccia et al., 2023). Companies do not perceive the importance of measuring the circular strategies implemented thus, are unable to communicate the value generated to their stakeholders. Nevertheless, the growing interest in CE has compelled investors, regulators, and other financial stakeholders to establish screening and eligibility criteria to comprehend how companies contribute to CE and sustainability (Opferkuch et al., 2023). Thus, companies need structured guidance for CE valorization, meant as its assessment and communication. However, it is crucial to note that 'circular' does not inherently mean 'sustainable.' To avoid burden shifting, it is essential to assess and monitor the strategies implemented (Luthin et al., 2023). The challenge is particularly pronounced in the context of Agri-Food Systems, as existing circularity metrics often target technical cycles, making them less suitable for AFS based on organic cycles (Moller et al., 2023). Moreover, in providing an overview of the circularity indicators applicable to the AFS, Poponi et al. (2022) caution against using single indicators without considering burden-shifting phenomena, which involves transferring issues to another stage in the supply chain. To establish more robust measurement approaches, several studies suggest a combined approach that includes indicators with already developed methodologies, one of the most cited is life cycle assessment (Stilitano et al., 2022; Falcone et al., 2022). Given the relevance of AFS in the global context and its specificities, it is necessary to identify an assessment approach targeted for the sector. Some frameworks for measuring circularity have been proposed for the AFS (e.g., Agnusdei et al., 2023; Pagotto and Halog, 2016). However, what is lacking in the AFS is a framework able to guide companies towards CE assessment and communication of the circular value generated to stakeholders. The main research question is therefore:

RQ3 How can companies of the AFS assess and monitor the circularity and sustainability of their activities?

1.6.2 Methods and validation

To improve the knowledge about how companies of the AFS can assess and monitor the circularity and environmental sustainability of their activities and provide guidance for the assessment two methods were adopted: a case study analysis and framework design.

To overcome the research gaps identified and understand the real issues of a company of the AFS, the present chapter proposes a case study analysis. Given the significant number of scientific contributions on CE in the Italian AFS that emerged in the literature review conducted (Chapter 2), Italy was considered a suitable context to analyse. Specifically, the case study is based on the cooperative *Fattoria della Piana*, known for its best practices in circularity and industrial symbiosis, located in the South of Italy.

The anaerobic digestion and combined heat power generation plant (AD-CHP) plays a central role in the development of symbiotic relationships within and outside the cooperative. The plant allows waste and scrap to be shared to give them the opportunity to become input resources for the digestor. The choice of company and the primary data collected are the result of a six-month internship at the company, as a compulsory component of this PhD scholarship.

The case study analysis outcomes were then used as input in the design of a framework to guide companies of the sector towards an effective assessment and communication of the circular strategies implemented.

1.6.2.1 Case study analysis

To support the company in quantifying the environmental and circular performance, this preliminary study started from analyzing the AD-CHP plant as the core of the closing energy and waste loop the cooperative and center of the symbiotic relations with partner companies. The assessment approach adopted is based on selected circularity indicators and supported by the LCA method is proposed. In this process, the company will evaluate not only the circularity level of the adopted strategies but also the environmental performance associated with the biogas plant and the materials used.

The circularity indicators were carefully chosen based on previous literature on the micro-level of circularity assessment in the AFS context. Ultimately, some indicators were selected and included such as Biogas efficiency (Mancini and Raggi, 2021), Recovery of energy by waste use, and Energy self-sufficiency (Poponi et al., 2022). The LCA is conducted in accordance with the ISO 14040 (ISO, 2006) standard and is articulated in four main stages: i) goal and scope definition; ii) life cycle inventory analysis; iii) life cycle impact assessment; and iv) interpretation of results. The functional unit (FU) chosen is 1 MWh of electricity produced. The system boundaries cover a “gate-to-gate” perspective, including i) the Anaerobic digestion process; ii) the Digestate management; and iii) the power and heat cogeneration in the CHP unit. Data related to the production process was primarily collected and is relative to the year 2022, while background and missing data are extracted from scientific literature and databases.

1.6.2.2 Framework design

The aim of the framework is to develop a CE assessment and communication framework for agri-food companies. The framework is built on the critical analysis and synthesis of the systematic literature review (Chapter 2), the survey and interview analysis (Chapter 3), and the case study analysis (Chapter 4) outcomes. Due to the diverse contributions in the field of CE measurement and implementation, this framework was designed by adapting existing methodologies to the specific context of the agri-food sector. The primary objective is to provide guidance to companies in this sector on the adoption of CE while avoiding the introduction of unnecessary complexity to the existing framework. Thus, the gaps identified in the above-mentioned chapters, allowed to determine the desired objectives for the framework, namely:

i) modularity, to provide flexibility in the selection of desired steps;
ii) being built on existing assessment tools;
iii) multi-dimensionality, to enable holistic assessment and
iv) adaptability to company characteristics, e.g. Select indicators pertaining to the company's activity companies.

Then a descriptive literature review of previous examples of CE assessment and communication at the company level is adopted to collect studies in line with at least one of the formulated objectives. Furthermore, to improve the solidity of the analysis, two standards for the adoption of circularity (BS8001, 2017; AFNOR, 2018) and four contributions (S&P Global, 2023; Becchetti et al., 2022; Opferkuch et al., 2023; Arana-Landin et al., 2023) were considered due to their relevance for the aim of the framework. Material collected is then adjusted for AFS's context and incorporated into the final framework. Finally, a validation of the framework through interviews with four companies of the AFS was performed. It is important to emphasise that this framework is preliminary, there are still aspects to be refined, especially regarding the social component.

1.6.3 Scientific contribution and thesis output

The analysis of the case study is expected to identify valid tools for evaluating the level of circularity and the environmental performance associated with the circular strategies implemented by the company. The analysis is limited to an exemplary case study to understand the needs and obstacles arising from an effective implementation of circularity. This fosters the sharing of circular best practices, but also a practical guide to evaluating circularity from an environmental perspective. However, to have a complete assessment of circularity, it is still necessary to include the economic and social aspects and to identify valid assessment tools. The final framework aims also to underscore the importance of communicating the generated value to stakeholders. Considering the CE as a component of environmental sustainability, raising awareness and effective communication are vital. The significance of the framework will lie in addressing the current absence of well-established reporting formats incorporating CE principles among companies in the sector (Falkenberg et al., 2023). With the advent of the new CSRD (European Commission, 2022) and EU Taxonomy (European Commission, 2020), companies will be compelled to articulate their circular and sustainable strategies to avoid CSR reporting becoming a competitive barrier. Despite its potential, the framework is under development and will be additionally improved by testing on a real case study as the next step.

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1.8 Deliverables of project

Table 1: Publications as a lead author

Type	Title	Authors	Publication outlet	Reference
Journal article	The maturity level of the agri-food sector in the circular economy domain: A systematic literature review.	Scandurra, F., Salomone, R., Caeiro, S., & Gulotta, T. M.	Environmental Impact Assessment Review,	Scandurra et al., 2023
Conference proceedings	Circular economy practices in the agri-food sector: an exploratory survey regarding Portuguese companies.	Scandurra, F., Salomone, R., Caeiro, S., & Pinto de Moura, A.	Proceedings ISDRS Conference 2023	Scandurra et al., 2023
Conference proceedings	Circular Economy Practices In The Agri-Food Sector: Awareness And Maturity Level In Portuguese Companies.	Scandurra, F., Salomone, R., Caeiro, S., & Pinto de Moura, A.	Proceedings Wastes – Solutions, Treatments and Opportunities 2023	Scandurra et al., 2023
Conference proceedings	Circular Economy Practices in the Agri-food Sector: A literature review	Scandurra, F., Salomone, R., Caeiro, S., & Mondello G.	Proceedings ISDRS Conference 2022	Scandurra et al., 2023
Conference proceedings	Circular Economy in the agri-food sector: an environmental and social analysis from Portuguese companies.	Scandurra, F., Salomone, R., Caeiro, S., & Pinto de Moura, A.	Proceeding AISME 2023	Scandurra et al., 2023

Table 2: Articles in progress or under revision.

Type	Title	Authors	Publication outlet	Status
Journal article	Circular economy in the agri-food sector: Insights into Portuguese companies' practices.	Scandurra, F., Salomone, R., Caeiro, S., & Pinto de Moura, A.	Circular Economy and Sustainability	Under review
Journal article	Assessing circularity and sustainability in the agri-food sector: A case study to framework design	Scandurra, F., Salomone, R., Caeiro, S., & Mondello G.		In progress

1.9 Attended scientific conferences

Table 3: Scientific conferences attended.

Date	Location	Event	Title of presentation
14/11/23-16/11/23	Rome, Italy	AISME Conference 2023	Circular Economy in the agri-food sector: an environmental and social analysis from Portuguese companies.
04/09/23-06/09/23	Coimbra, Portugal	Wastes Conference: Solutions, Treatments and Opportunities	Circular Economy Practices In The Agri-Food Sector: Awareness And Maturity Level In Portuguese Companies.
11/07/23-13/07/23	Kuala Lumpur, Malaysia	29th International Sustainable Development Research Society (ISDRS) Conference 2023), Universiti Kebangsaan Malaysia (UKM), Malaysia	Circular economy practices in the agri-food sector: an exploratory survey regarding Portuguese companies.
28/06/23-30/06/23	Milan, Italy	Italian LCA Network (Rete italiana LCA) 2023	NA
14/06/22-17/06/22	Stockholm, Sweden	28th International Sustainable Development Research Society (ISDRS) Conference 2022)	Circular Economy Practices in the Agri-food Sector: A literature review

Chapter 2 The maturity level of the agri-food sector in the circular economy domain: A systematic literature review[1]

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The maturity level of the agri-food sector in the circular economy domain: A systematic literature review

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ABSTRACT

The agri-food sector (AFS) is crucial in the transition towards sustainability. The Circular Economy (CE) has gained global attention as a tool to achieve it systemically. Nevertheless, it is necessary to understand the maturity level of circularity in the AFS. For that reason, this study aims to analyse, through a systematic and bibliometric literature review, examples of circularity in the sector at inter- and intra-company levels, considering case studies with a micro or *meso* perspective of analysis. The review was conducted using Scopus and Web of Science databases, identifying 43 peer-reviewed articles published from 2015 to the end of February 2022 and 162 practices. The review explored the maturity level of the agri-food sector in terms of circularity through the innovativeness of its practices. Results show that 51% of the practices have a conventional nature, whereas incremental and radical innovation represent 46% and 3% of the sample. The analysis also investigated, through content analysis, the links with Industrial symbiosis (IS), and sustainability, which remains poorly explored, especially in social terms. Although some limitations are present due to the research criteria, the study allows for deep diving into the characteristics of circularity in the sector by contributing to the definition of a database of circular best practices capable of driving practitioners towards its application and capturing challenges and potential ways of improvement.

1. Introduction

Nowadays, worldwide food production is driven by the linear paradigm of "take-make-use-waste", which enabled the agri-food sector (AFS) to be more resource-intensive but less sustainable. There are several definitions of the AFS. According to the Food and Agriculture Organization of the United Nations (FAO), it is a system that "…covers the journey of food from farm to table including when it is grown, harvested, processed, packaged, transported, distributed, traded, bought, prepared, eaten and disposed of. It also encompasses non-food products that also constitute livelihoods and all of the people as well as the activities, investments and choices that play a part in getting us these food and agricultural products" (FAO, 2021, page 3).

Currently, Food Losses and Wastes (FLW) characterize one-third of food produced globally (Fassio and Tecco, 2019). Specifically, food loss is any reduction that occurs from harvesting to retail, while food waste is the reduction from retail to consumption phase (FAO, 2019). In addition, the increase in the population level requires the AFS to adequate its productive patterns to feed the additional 2 billion people expected by 2050 (Toop et al., 2017). Food production and consumption directly impact food safety and quality and indirectly impact the environment, affecting overall human health (Gibin et al., 2022).

In this context, Circular Economy (CE) is observed as a possible solution to preserve resources and reduce the negative externalities caused by the production systems, including the agri-food sector, favouring the transition to Sustainable Development (SD) (Esposito et al., 2020). CE is a holistic approach to development, regenerative by design and able to decouple resources exploitation from economic growth (EMAF, 2015). CE principles are not new in the AFS and can be retraced back in the agri-food dynamics. One clear example is the "Farming bricolage" in peasant society, where all edible residues are reinvented in the next meal to eliminate waste (Fassio and Tecco, 2019). To guide the transition to SD in the AFS, it is necessary to understand how the sector implements circularity by exploring intra- and inter-company synergies. The intra-firm dynamics can be captured by analyzing the practices implemented in single organizations (micro perspective), whereas the inter-

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0195-9255/

firm ones by investigating the relations among different companies, (*meso* perspective). The latter dimension may configure as an example of Industrial Symbiosis (IS), aiming to embrace different entities towards competitive advantage through exchanges of residues, water, and energy (Chertow, 2000). The connection between CE and IS is not new. For example, in Europe, the Action Plan (European Commission, 2015) directly addresses the role of IS in transforming the linear system (Domenech et al., 2019).

Therefore, CE has a strategic role in reaching SD, but the connection is still unclear. Circularity is indeed ruled by eco-efficiency, which is not free from rebound effects and thus CE may not coincide with sustainability. SD implications (economic, environmental, and social dimensions) of circular and symbiotic solutions are still debated and particularly relevant in AFS (Stillitano et al., 2021). A relevant lack suggested by the literature is the non-explicit social commitment of CE. Sustainability pursues society's well-being and the safeguarding of human rights, while CE considers social improvement mainly in terms of employment (Murray et al., 2017). In the AFS, food lies at the core of the human relationship with nature, generating a cultural value which cannot be underestimated (Fassio and Tecco, 2019).

A theoretical overview conducted to highlight the main lacks in the literature on the topic (further details are available in the supplementary materials) shows that the study of CE in the agri-food context is widespread in the literature. Indeed, in the last years, several authors addressed its application, i.e. through studies on CE in the agricultural supply chain, e.g.: i) describing existing practices and possible future scenarios (Esposito et al., 2020), ii) detecting the political and social dimension (Hamam et al., 2021), or iii) highlighting the role of reuse and valorization strategies of waste and by-products (Chiaraluce et al., 2021). Even though circularity is already present in the sector, the challenge to establish an appropriate classification for circular practices in the food system is still open and needs to be filled. Several examples of classification are present in literature (Papargyropoulou et al., 2014; Vandermeersch et al., 2014; Rood et al., 2017); nevertheless, none of them is focused on assessing the maturity of the sector in terms of circularity.

In this context, the present research proposes a systematic literature review (SLR) focused on the *meso* and micro level of circularity practices, considering their earlier stressed context, in the AFS by addressing the research question (RQ): What can we learn from inter- and intra-organization practices and experiences of Circular Economy in the Agri-food sector to assess the circular maturity of the sector? This SLR specifically holistically explore the CE practices of the AFS from an environmental, social, and economic point of view. In particular, the research examines the practice's characteristics, analyzing their goals and innovative or traditional nature to understand if these circularity practices are innovative or traditional, can be connected to IS and if and how they contribute to SD.

After this introductive section, the paper is organized as follows: Section 2 describes the methodology adopted to perform the literature review, exploring in detail the research approach employed for collecting the studies. Section 3 presents the results obtained through the systematic and bibliometric literature review. Section 4, discuss and critically analyse the findings of the literature review. In conclusion, section 5 summarizes the main findings of the analysis and points out future research opportunities.

2. Methods

A bibliometric and systematic analysis of the existing scientific literature was conducted to answer the research question. The bibliometric analysis explores texts, focusing on information regarding authorship, affiliation, collaborations, and keywords while examining the linkages between and among studies (Geissdoerfer et al., 2017). This enables an understanding of how the interest in the topic has evolved in time and space. On the other hand, systematic reviews set clear and explicit research criteria to identify all the evidence in line with the research questions enabling the generation of a picture where bias is minimized and reliable findings are provided (Snyder, 2019). Given the importance of providing a standard peer-accepted methodology, increasing the consistency and robustness as well as the replicability of the analysis, the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) method is selected as the formal guideline of the present study (Page et al., 2021). The procedure applied for this literature review is summarised below, explaining first the applied search procedure for identifying the literature case studies and then the macro categories of data extracted from each.

2.1. Database search strategy

The search strategy applied is summarised in Fig. 1, showing: i) the keywords and databases employed to identify the sample of articles, ii) the inclusion and exclusion criteria used during the double-screening process, and iii) the final sample of articles and the practices selected for the analysis.

In particular, the research was carried out by searching for keywords capable of qualifying empirical examples of CE (such as "circularity" OR "circular economy") in the Agri-food sector ("Agri-food", OR "Food" OR "Agrifood" OR "Agri food" OR "Agriculture"), within the databases Scopus and Web of Science. This choice guarantees that high-level quality articles were included in the analysis, which is a fundamental issue in examining the state of the art of the research topic. In addition, according to Crowe et al. (2011), the term "case study" is added to the search query, allowing an in-depth analysis of the phenomenon observed in its natural context. The research was conducted first on 28 September 2021, second on 31 December 2021, and third on 28 February 2022. All search queries are reported in the supplementary materials (File Excel - Worksheet "Search queries"). This research allowed for identifying 502 articles (Fig. 1) that were reduced by applying the database search filters to select:

- only articles published from 2015 to 28 February 2022 in English. The starting date of 2015 was chosen due to the introduction of the "Closing the Loop: An EU Action plan for the Circular Economy Package" by the European Commission (European Commission, 2020) in December 2015.
- only peer-reviewed articles, excluding items such as reviews, book chapters, conference papers, books, conference reviews, etc. This choice allows for considering only on original high-quality contributions on the topic.
- only research fields in line with the scope of the study were included (excluding fields such as computer science, mathematics, arts and humanities, immunology, psychology, etc.).

After the filter application, the bibliometric data of the remaining 198 articles were exported on Microsoft Excel software to identify and eliminate duplicates (60). Then, a double-screening process was applied to identify only the studies addressing the selected eligibility criteria outlined in Fig. 1.

During the first screening, 87 studies were selected based on title, abstract and keywords, excluding the articles considered out of the scope of the analysis (e.g., papers that i) focus on topics different from CE, such as poverty alleviation, ii) described CE practices not in the agri-food, such as in the industrial solid waste, iii) did not study specific practices, like the analysis of the spatial distribution of biogas production potential, etc.).

The remaining articles were downloaded for the second screening for the full-text evaluation, selecting only articles: i) presenting case studies (e.g., reviews are excluded), ii) describing practices linked or attributable to CE, linked to the agri-food sector, iii) having a micro or *meso* level of analysis. The final sample was then of 43 articles. From the final sample, 162 circular practices were identified. All the practices labelled

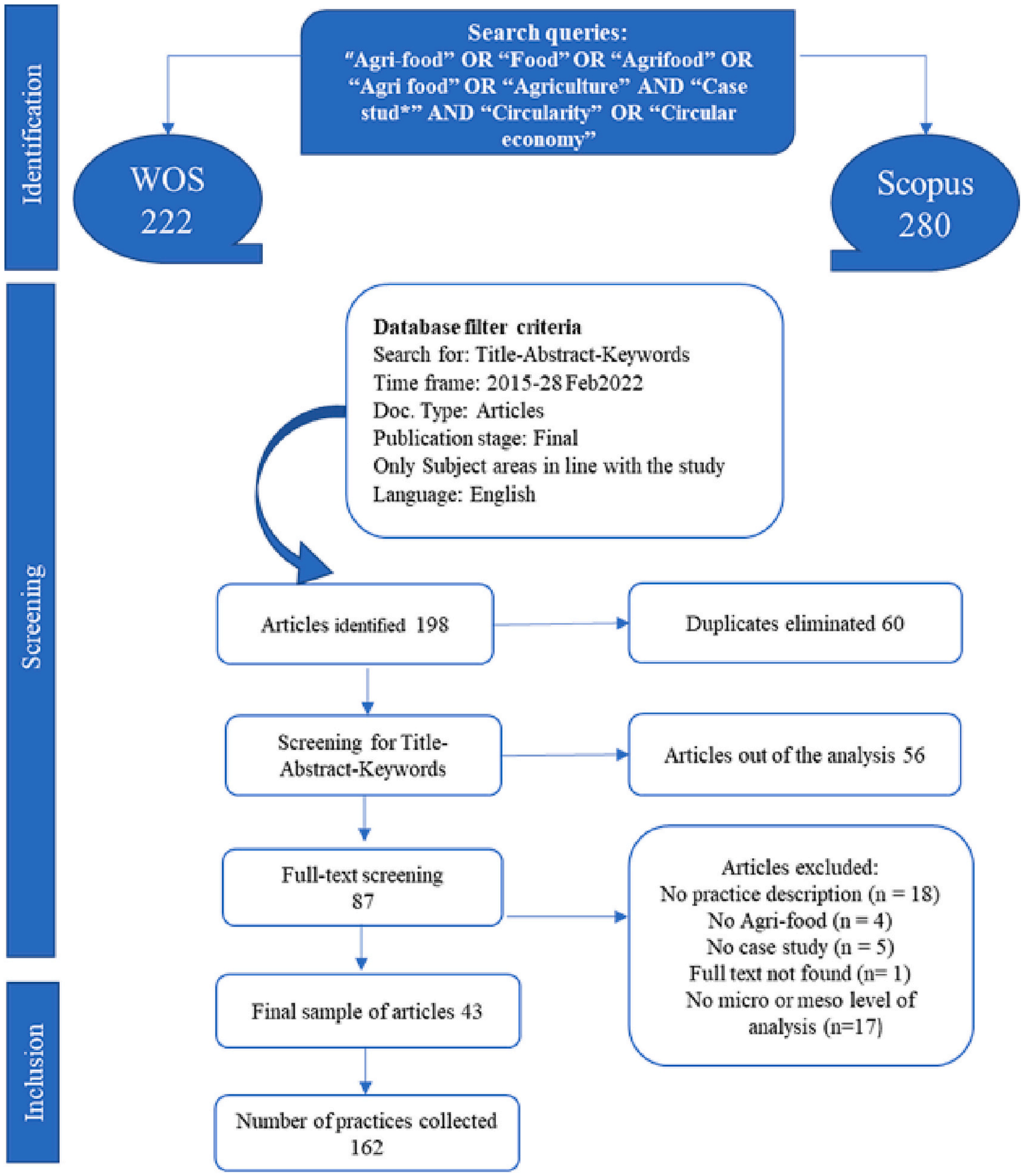

Fig. 1. Flow chart diagram of the database literature search procedure.

as circular or in line with circularity principles are included. Based on this definition, some studies present more than one practice because, for example, in studies focused on the micro level, different scenarios of the same practice have been compared, while in the meso level, more circular practices have been presented in the same organization resource management. All the data collected during the analysis are reported in the supplementary materials.

2.2. Macro categories analysis

The sample analysis was carried out according to 4 macro-categories: 1) Bibliometric information, 2) Context of the studies, 3) Agri-food practices description and classification and 4) Sustainable narratives.

2.2.1. Bibliometric information

This category allows for measuring the level of interest in the topic, contributing to the analysis of circular practice in the sector. It includes bibliometric information regarding the title of the contribution and authors, the year of publication, the journal source, as well as the subject area covered by the journal. All the data regarding the studies extrapolated from Scopus and WOS. Only for the subject area, the definitions proposed by Scopus were adopted to increase the level of uniformity.

2.2.2. Context of the studies

This category considers the number of practices identified and enables to capture of the main characteristics to understand what is possible to learn from such examples of circularity. It includes information regarding the characteristics of the studies in terms of geographical setting, analyzing both country and continent level and supply chain, considered in terms of typology (e.g., agriculture, dairy, livestock, etc.) and stage (namely production, processing, consumption, etc.). In addition, when the case studies respond to multiple typologies of supply chain, the category "various" was adopted.

2.2.3. Agri-food practices description and classification

This category considers the number of practices collected among the sample of articles and allows for exploring and classifying the practices implemented according to a) innovative or traditional nature and b) level of circularity.

In particular, food practice's categorization organizes the practices per process and goal and is depicted in Table 1. In this case, the coding framework employed for the analysis was developed by adapting existing waste food frameworks. The classification process must consider those issues overlooked by the current waste framework European Commission, 2008. For example, it is focused on prioritizing end-of-life treatments, neglecting more sustainable options like prevention or reuse. In addition, the hierarchy has a general scope, which gives space to personal interpretations by actors and institutions, limiting the capacity to address environmental challenges (Teigiserova et al., 2020). This explains the need to define frameworks able to entail the main characteristics of the food sector, broadening the valorization pathways and, thus, generating positive incomes on an environmental, economic, and social aspect.

Meanwhile, the level of innovativeness classifies practices as conventional, incrementally innovative, or radically innovative and is depicted in Table 2. The transition to circularity requires both incremental and radical changes in a coordinated and integrated way along with the whole food system. The study tries to capture the nature of such innovation, analyzing if the practices detected have a technological or socio-organizational form (Potting et al., 2017). The first describes an innovation focused on technology as a core characteristic, while the latter aims to review the socio-organizational codes and adopt new beliefs and perspectives of action.

2.2.4. *Sustainable narratives*

Considering the number of studies, this category enables to understand how the studies describe CE and if they are connected to IS and sustainability. The narrative is analyzed following three perspectives: circular economy, industrial symbiosis, and sustainability (see Table 3).

Table 1
Categorization of the food practices per process and goal.

Food practices's categorization			
Process classification	Practice Goal	Description	References
Optimization of the production process	Material in inputs	Optimization in materials use	Papargyropoulou et al., 2014
	Energy in inputs	Optimization in energy use	
	Technologies	Optimization concerning the technologies employed	
Sharing of resources	Tangible	Sharing of tangible resources, e.g., agricultural inputs, energy, food, animal feed, etc.…	Rodrigues et al., 2021
	Intangibles	Sharing of intangible resources, e.g., knowledge, responsibilities, labour, etc.…	
Reprocessing	Nutrients Feed Food Pet food Energy Materials Water	Any operation/ process by which waste food is reprocessed into fuel/ energy/raw materials/value-added products	Garcia-Garcia et al., 2017
Incineration and Landfilling	With biogas recovery	Waste disposal on landfills or incineration	Garcia-Garcia et al., 2017/ Rood et al., 2017
	Without biogas recovery	–	

Table 2
Classification of practices per level and nature of innovativeness.

Innovativeness's level and nature		
Innovativeness level	Description	References
Conventional	Conventional practices are operations and processes well-established in the literature, e.g., agroforestry, inter-cropping, crop rotation, cover cropping, traditional organic composting, and integrated crop-animal farming diversification, soil management, soil conservation, grass strips and living barriers.	Singh and Singh (2017); Altieri and Nicholls (2017)
Incrementally Innovative	All those activities that privilege technological and productivity-oriented innovations to guaranteed resource-efficiency. These kinds of innovations allow the existing products and processes to continue being competitive, but also to be competence enhancing, since they are based on existing knowledge.	HLPE Report (2019); Afuah (2003)
Radically Innovative	All those practices that aim to redesign the food system, entailing a territorial vision, while considering environmental, social, and economic conditions. They generate products that render the existing ones non-competitive, creating also new knowledge, that overcomes the existing one.	HLPE Report (2019); Afuah (2003)
Technological Innovation	Innovative practices for which the technological aspect plays a core role in the transition process.	Potting et al. (2017)
Socio-organizational Innovation	Innovative practices for which the social and organizational aspect play a core role, aiming at long-term change in society's customs and beliefs.	Potting et al. (2017)

The analysis was performed by adopting the content analysis technique. Such qualitative methodology enables the interpretation of text data through a coding process, which discloses research themes and patterns in the text under evaluation (Moldavska and Welo, 2017). In particular, the following considerations were made for:

a. Circular economy. The category investigates firstly if and how the studies define CE, measuring it in terms of "mentioning units"; deep diving into the level of explanation and analysis adopted by the single study. CE is further analyzed through the R framework. The framework summarizes the main circular "actions" (Ghisellini et al., 2016); it was first declined into the 3 Rs form (Reduce, Reuse and Recycle) (Zhu et al., 2019). Nowadays, different forms of the framework exist; the most nuanced includes the 9 Rs (Potting et al., 2017). The present study adopts the 4Rs framework to assess the level of circularity. This configuration was chosen since it was employed in the European waste directive (European Commission, 2008), so it is well-known.

b. Industrial Symbiosis. The present study considers the industrial symbiosis (IS) as part of the CE concept (*meso* level). IS impact on AFS practices has been included since different symbiotic relations have been identified in the sample. The analysis identifies the direct mention of the term industrial symbiosis within the articles considered.

c. Sustainability. To assess the connection between sustainability and circular economy, the sustainability "mentioning unit" is expressed as a direct mention of the term "sustainability" and "sustainable development" in the text. This analysis enables us to understand if sustainability is perceived as linked to circularity or as a stand-alone principle within the sample. The study considers the sustainability pillars adopted by the single articles, considering environmental quality, economic prosperity, social equity, or a combination of more of them.

Table 3
CE's contextualization level and linkages with IS and SD.

Level of contextualization					
Circular Economy		Industrial Symbiosis		Sustainability/Sustainable Development	
Mention	Description	Mention	Description	Mention	Description
Not contextualized	Studies in which the term CE is only mentioned as a keyword, or present in the abstract	Not mentioned	Studies in which the term IS is not directly mentioned in the text	Not mentioned	Studies in which the terms Sustainability or SD are absent in the text
Mentioned	Studies that provide a definition of circularity or directly mention its principles as defined by Kirchherr et al. (2017)	Mentioned	Studies in which the term IS is indirectly mentioned.	Not contextualized	Studies in which Sustainability or SD are not directly mentioned, or only mentioned as keywords, or present in the abstract
Linked to other sustainable streams	Studies that link the circularity to other sustainable thinking streams, excluding of sustainability and IS (treated in detail in the next sections)	Linked to CE	Studies that link IS to CE	Mentioned	Studies that provide a definition of Sustainability or directly mention its principles as defined by WCED (1987)
				Linked to CE	Studies that link Sustainability with circularity

3. Results

In this section, the results of the bibliometric and systematic analysis are discussed. In addition, a critical analysis of the main methodological and technical characteristics of the final sample of articles is provided.

3.1. Bibliometric analysis

The bibliometric analysis is carried out by evaluating a) the yearly distribution of publications, b) the journal source, and c) the research area covered by the journal source. In particular:

a) Considering the yearly distribution, the sample contains 43 studies published between 2015 and the end of February 2022 (Fig. 2). The highest number of publications was registered within 2020–2021, representing 63% of the total sample. Nevertheless, not considering the beginning of 2022, the number of studies has more than doubled during the last years of observation, indicating the growing attention of academia on the topic.

b) Regarding the publishing sources, 25 scientific journals are identified in the sample (Fig. 2). The primary journal source is "Journal of Cleaner Production", which published 10 studies within the period analyzed, showing a constant interest in the topic. The main secondary contributors are "Science of the Total Environment" and "Resource, Conservation and Recycling", both publishing 4 articles. The first has increased the attention in the field only in the last two years, while the latter has shown a steady interest. It is relevant to notice that 19 out of 25 Journals published just one study on CE in

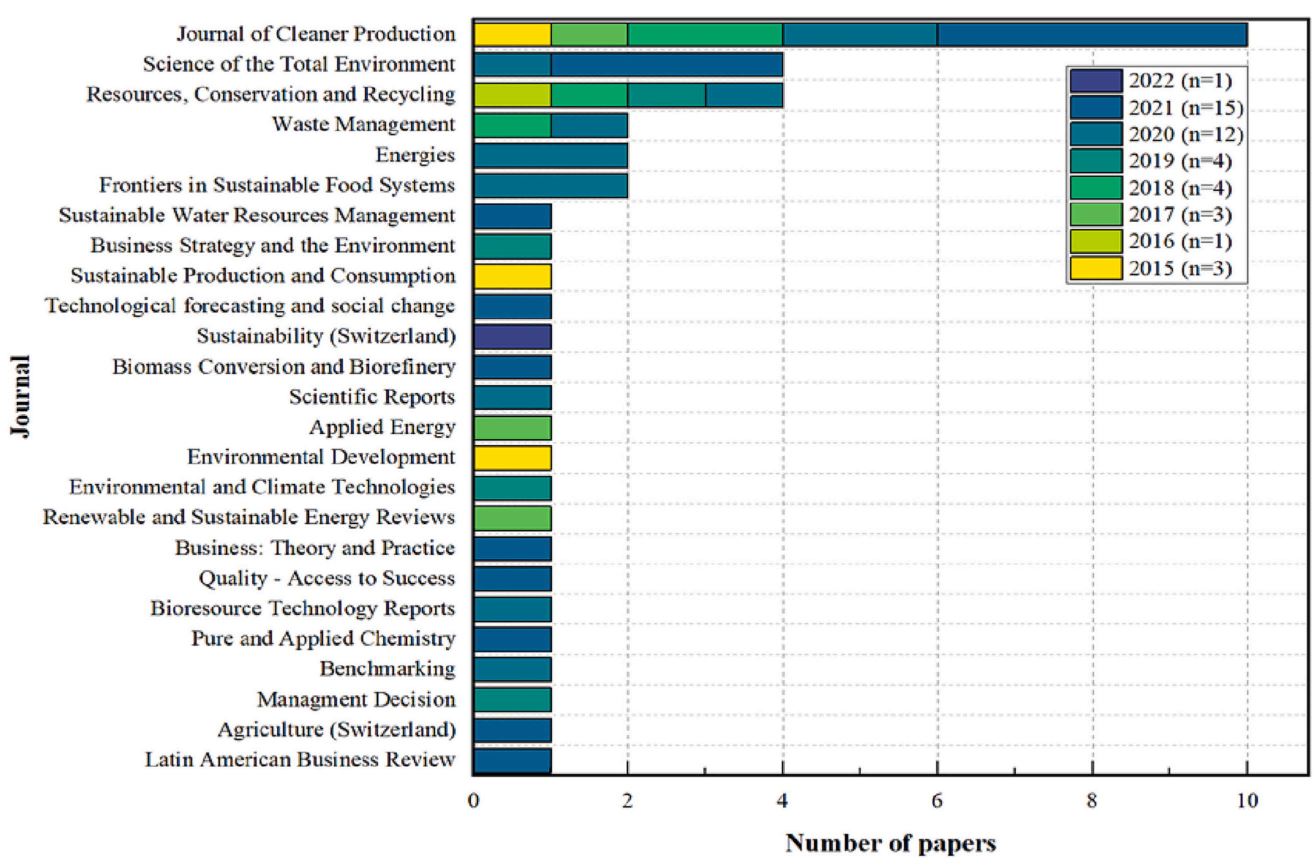

Fig. 2. Number of articles per year and journal.

AFS. These findings are summarised in Fig. 2, analyzing the trend of the topic based on the annual distribution of publications and journal sources.

c) The analysis for the research area per journal confirms the strong environmental vocation of the field, the most recurrent area is “Environmental Science”, which represents 25.5% of the total areas identified. It is important to mention that the number of articles does not match the final number of publications in the sample because a study can be connected to more research areas. The second area of interest is “Energy”, followed by “Business, Management and Accounting” and then “Engineering” and “Social sciences”.

3.2. Context of the studies

This section reports the results linked to the geographical setting as well as the studies' supply chain type and stage. Fig. 3 shows the number of articles per country and continent setting, and the matrix presents the number of practices in terms of supply chain type and stage.

3.2.1. Geographical setting

First it is analyzed the geographical setting, namely where the studies were developed. It is relevant to highlight that some studies are settled in more than one country (Italy-Spain and Brazil-United Kingdom). As summarised by Fig. 3, European studies represent 61% of the sample. Italy's role is prominent contributing to 28% of the total sample. The United Kingdom and Spain are the second-largest contributors among the other European countries, with 4 and 3 publications. Moving to Asia, China maintains a leading role, publishing 4 studies on the topic. Other contributions were identified in Malaysia, Singapore and Turkey. South American publications are dominated by Brazil, which presents 6 studies. North and Central America, as well as Africa show just 1 publication each.

3.2.2. Supply chain type and stage

The analysis of the context also entails the supply chain (SC) type and stage. These findings are summarised in Fig. 3 and quantified for practice. In terms of the typology of the supply chain, agriculture showed the highest number of publications describing 48% of the practices. In detail, Italian agricultural studies present 39% of the practices of the category, while Brazilian ones 25%. The “Various” category is the second most reported, analyzing 26% of the practices. The least explored is fish breeding, characterizing 5% of the practices, all described by Spanish case studies.

Moving to the supply chain stage, the processing phase is the most relevant, representing 30% of the practices, where Italian practices represent 37.5% of the total. This is followed by whole supply chain practices, representing 40% of which 27.5% have a Brazilian setting. The least treated stages are consumption and retail. The consumption stage characterizes the 3% of the circular practices in the sample, which are all settled in Costa Rica. The retail sector is analyzed by 9% of the practices, and 65% of the category has an Italian setting.

3.3. Process classification

This section includes the classification and critical analysis of the practices and processes described by the articles based on the earlier theoretical overview (Section 2.1). As mentioned above, the number of practices does not match the number of articles since the studies may describe more than one “circular” process. The sample includes 162 practices out of 43 articles defined as or linked to CE in the AFS. All characteristics of practices are summarised in Fig. 4.

3.3.1. Process and goal of the practices

Reprocessing processes characterize 66% of the practices. The subcategory Energy reprocessing characterizes 39% of the category. The agriculture supply chain is the most involved in the sample, characterizing 43% of the subcategory. Within reprocessing, the production of nutrients is a relevant goal. It is considered by 25% of the category. Once again, agriculture is the most involved chain, describing 52% of residues and by-products, while more engaged stages are the productive (41%) and end-of-life (22%). Another relevant section is represented by Materials reprocessing. It represents 15% of the. 69% of the practices are linked to the agricultural field, especially in terms of processing (56%). Optimization processes represent 19% of the sample and are analyzed by 10 studies. They mainly focus on optimizing materials used in the inputs (71%). Technological optimization characterizes 22.5% of the category.

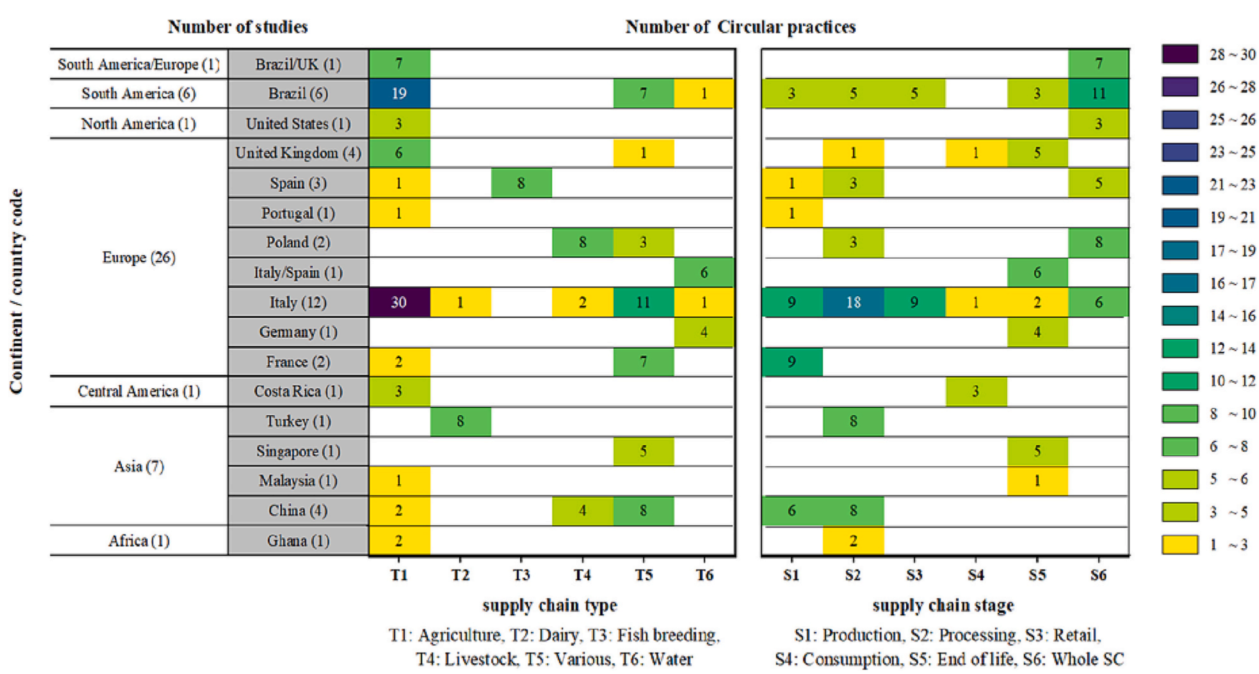

Fig. 3. Relations between the number of studies per geographical setting at the country and continent level (vertical axis) and the number of practices per supply chain type and stage (horizontal axis).

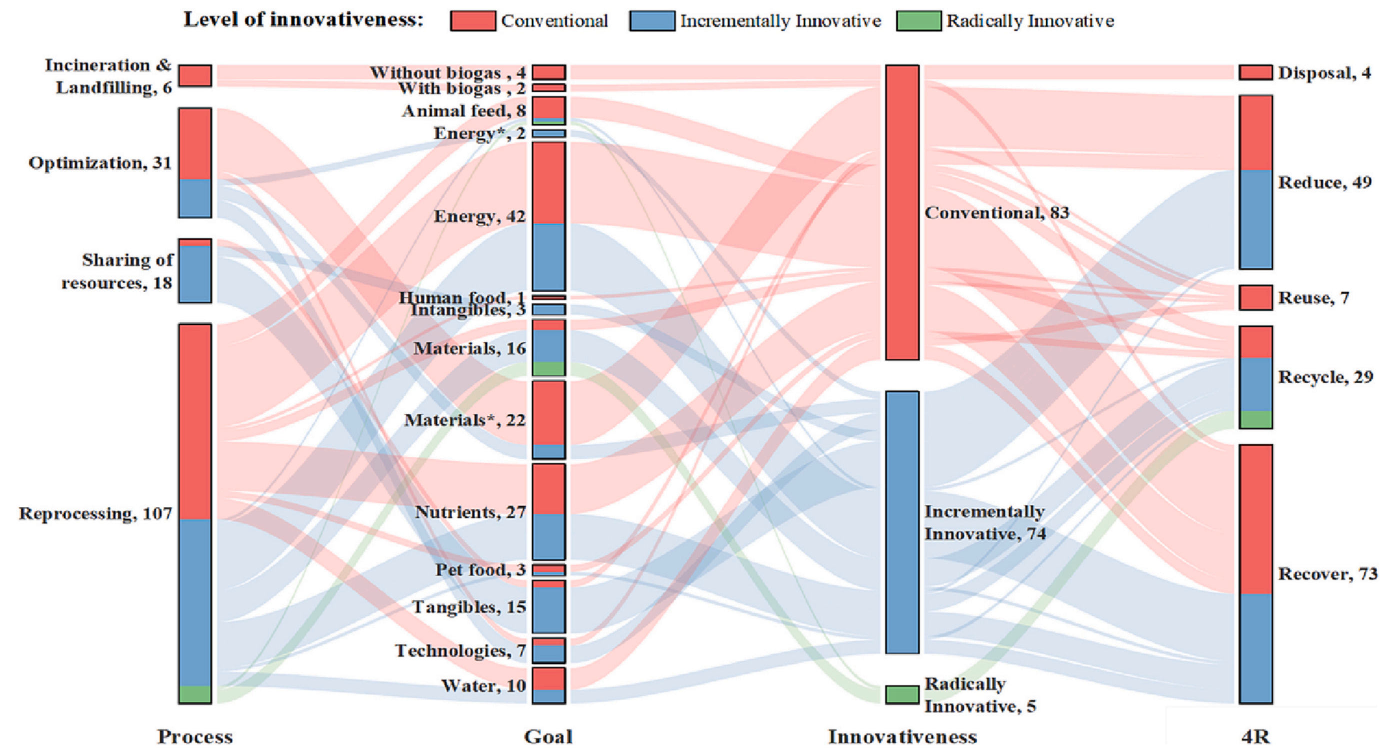

Fig. 4. Relations among process, goal and circularity with the level of innovativeness.

Resource sharing describes 11% of the total sample and is explored by 6 articles. Sharing practices are common at the agricultural level (78% of the category) and usually are considered in studies that analyse the whole supply chain (72%). Finally, incineration and landfilling characterize only 3.5% of the sample and 3 articles. The category considers both biogas recovery and not recovery. The latter represents the most common in the sample, but the least preferable option given the emissions connected.

3.3.2. Innovativeness of the practices

Conventional practices cover 51% of the sample. The category involves reprocessing processes (66%) directed to the production of energy (42%) or nutrients (25%). Relevant is the presence of optimization processes in the category, which represent 24% of the conventional practices, almost entirely directed to the valorization of materials (90%). These practices are linked to a wide variety of activities in terms of R framework; 51% of the subsample is related to recovery strategies, 25% to reduce strategies, 11% to recycle strategies and the remaining 8 and 5% to reuse and disposal strategies. In detail, 95% of recovery practices are related to reprocessing options. In comparison, the remaining 5% to incineration and landfilling, 95% of reduce strategies are linked to optimization processes, recycle strategies are full described by reprocessing operations, finally reuse strategies are linked to reprocessing (85%), while disposal options are all directed to incineration and landfilling. On the other side, incrementally innovative practices represent 46% of the sample. The practices entail 63% of reprocessing processes, directed to the production of energy (40%), nutrients (28%) or materials (19%). Sharing practices represent 22% of the subsample and are directed almost entirely to sharing tangible resources (81%); the remaining ones are related to intangible resources. Optimization practices represent another interesting portion of the sample (15%), directly linked to technological and material optimization in 45 and 36% of the cases. Analyzing the nature of innovation, technological innovations characterize 72% of the category, while socio-organizational one represents a still limited 22%. The remaining 6% of practices can be described as a mix of technological and organizational innovation. Regarding 4Rs, incrementally innovative practices are connected to recover strategies for 42%, reduce strategies for 38% and recycle ones for 20%. Specifically, recover and recycle strategies are associated entirely with reprocessing operations, while reduce ones are associated with sharing (57%) and optimization (40%) options. Radical innovation practices characterize 3% of the sample. These practices are entirely reprocessed into materials, and considering the nature of innovation, they pursue only technological innovation. Moreover, radically innovative practices are associated with recycling strategies.

3.4. Sustainable narratives

This section includes the results of the content analysis performed on CE, IS and sustainability following the measuring units chosen, summarised in Fig. 5 per number of studies and Fig. 6 per number of practices. This enables the articles 'classification according to their level of understanding of the sustainable narratives mentioned (Section 2.1), capturing how they are described and embodied and the possible links between them.

3.4.1. Circular economy

As evidenced by Fig. 5, most sample studies contextualize CE (51%) by adopting a definition or recalling its core principles. Different definitions of CE have been encountered in the sample, like the one provided by Kirchherr et al. (2017) or the one provided by Korhonen et al. (2018). These studies were settled mainly in the agricultural field; significant also is the number of studies dealing with fish breeding. 75 circular practices were connected to contextualizing papers, 43% of them follow recovery strategies, 27% reduce, and 17% recycle operations. The remaining 8% and 4% were linked to reuse and disposal options. Nevertheless, 37.5% of the studies did not characterize the concept, e.g., limiting to mention of it among the keywords or the abstract. These studies were settled in different supply chains, where the agricultural one is the most relevant. 55 practices were associated with these studies, of which 53% are classified as recovery strategies and 29% to reduce ones. The remaining studies (11.5%) combine circularity with other

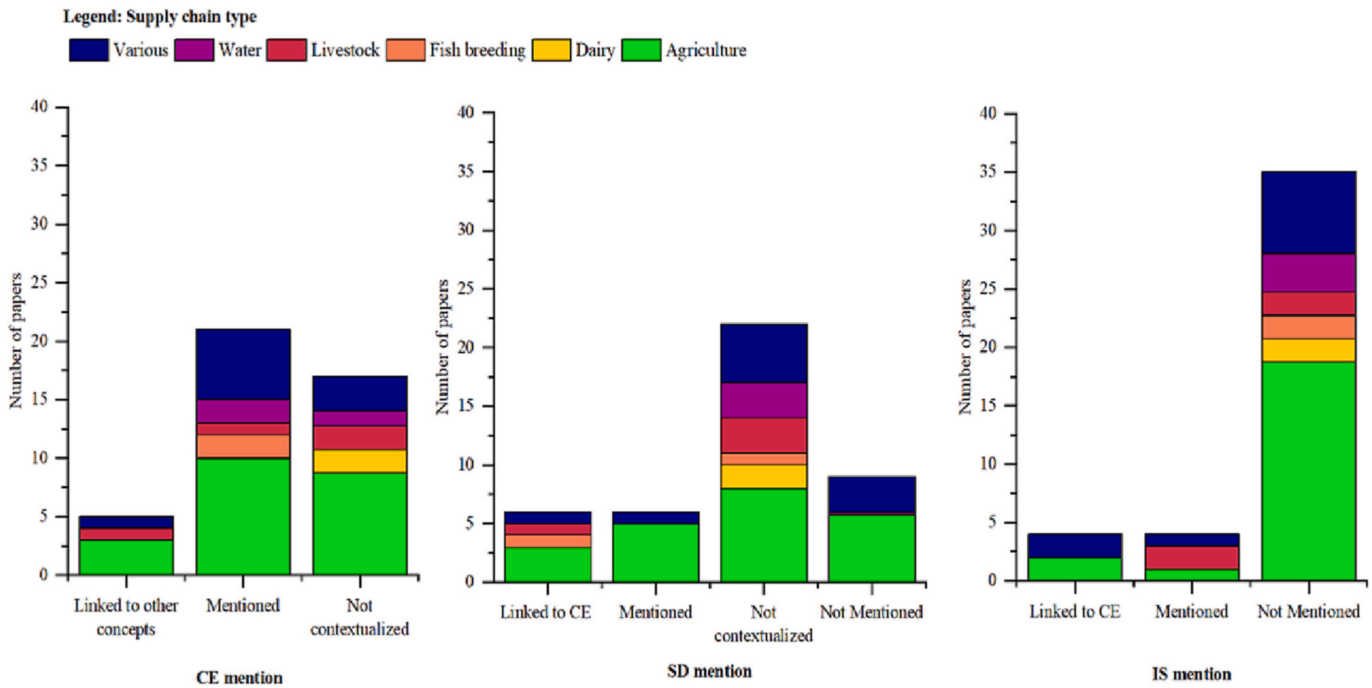

Fig. 5. Level of conceptualization of Circular economy (CE), Sustainable development (SD) and Industrial symbiosis (IS) per number of papers and supply chain type.

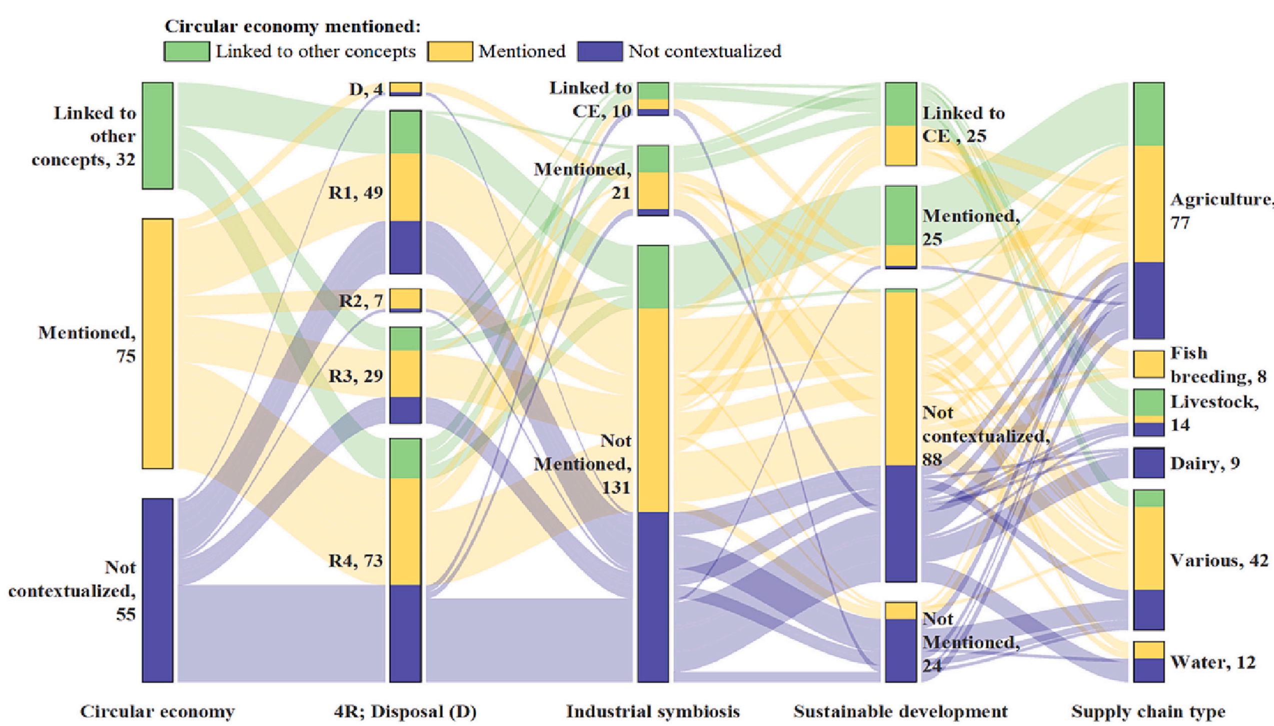

Fig. 6. Content analysis: Level of conceptualization of CE, IS, SD per number of practices per supply chain type and R framework.

sustainable narratives, emphasizing the similarities and connections. Ultimately, the link with the circular bioeconomy was evaluated by 2 articles. The link with the sharing economy is analyzed only by 1 study. In the end, the link with industrial ecology was addressed by 1 contribution. Such studies were settled only in the agricultural and livestock supply chain and in the residual category. They were associated with 32 practices, of which 40% are related to reducing strategies, while 37.5% are to recovery ones.

3.4.2. *Industrial symbiosis*

The analysis revealed that 9% of the articles directly mentioned the term “industrial symbiosis”. In detail, 21 practices were identified,62% of them were classified as recover, 19% as recycling and the remaining 14% and 5% are disposal and reducing operations. These studies were associated with the agricultural, livestock and various supply chain. Another 9% linked IS to CE. In this case,10 practices were identified, 90% were recovered, and the remaining 10% were recycling strategies. Such studies were settled in the agricultural supply chain and various categories. The remaining 82% of the studies did not include IS. In conclusion, 131 practices were identified among the studies that do not mention IS. In this case, 39% were recovering strategies, 37% were reducing, 18% were recycling, 5% were reusing and 1% were disposal ones. Here the agricultural supply chain prevailed as the setting of the studies.

3.4.3. Sustainable development

The analysis based on SD's link indicates that most articles of the sample mention the concept of sustainability without contextualizing it (51%), namely, without mentioning its principles or giving a definition of it. In this case, 88 practices were detected; 50% is connected to recovery options, 25% to reducing ones, 14% to recycling ones, and the remaining 7% and 5% to reusing and disposing. These studies showed applications in every supply chain type categorized. Besides that, another 21% of the sample did not mention the concept at all. These studies were associated with 24 practices. 46% of such practices were reducing operations, 33% recovering and 21% recycling ones. Here, the study setting was divided into the agricultural supply chain and the various category. The remaining studies linked sustainability to CE (14%) or mentioned the concept, contextualizing it (14%). 25 practices were identified for studies that link SD to CE; in this case, 48% is made of recover strategies, 32% by recycling operations and the remaining 16% and 4% by reduce and reuse operations. These studies were mainly settled in the agricultural supply chain. Whether studies that mention SD were associated with 25 practices, 48% pursue reduce strategies, 36% recover and the remaining 16% recycle. These studies were settled almost entirely in the agricultural supply chain.

In terms of pillars, there is a clear dominance of the environmental one. Considering those studies that mentioned or linked SD to CE, this dimension is present in all 12 studies alone (75%) or combined with other perspectives (25%). Indeed, the environmental pillar is combined with the economic dimension in 17% of studies. The less explored remains the social pillar, directly mentioned only by 1 study, which mentions all three pillars (Kowalski and Makara, 2021).

4. Discussion

The analysis showed a growing number of peer-reviewed articles on the topic. Such increase is easily explained by the numerous international measures implemented to foster circularity, such as the European Green Deal (European Commission, 2020), and, specifically, the Farm to Fork strategy (European Commission, 2020). The analysis emphasized the high level of fragmentation in the field, already been pointed out by Masi et al. (2017) and Esposito et al. (2020). Interestingly, this has gained the attention of journals with wide areas of research interest. The main area of research is linked to the environmental dimension, but there is a consistent presence of the economic dimensions, as well as areas, although limited, linked to the social sciences. This signals the progressive multidisciplinary nature of CE in the AFS. Thus, the bibliometric analysis has highlighted academia's increasing interest in applying CE to the AFS.

On the same line, the context analysis showed that the interest in the topic has spread geographically. The leading role of Europe confirms the relevance of the European Action plan (European Commission, 2015) in boosting attention on this topic. The key role of Italy could be explained by the numerous policy interventions adopted for circularity, e.g., law 211, adopted in 2015, which aims to contain excessive natural resource use (Ghisellini and Ulgiati, 2020). Nevertheless, new actors emerged from the analysis. Relevant is the role of Brazil in South America. The country has indeed introduced several initiatives for the sustainability of the AFS; for example, the Low-Carbon Agriculture Plan, launched in 2010, provides financial support to farmers who want to introduce sustainable agriculture techniques (Neate, 2013). Moreover, the interest of Asian countries remains; China, was the first to introduce CE at a policy level, but new Asian actors, namely Malaysia, Singapore, and Turkey, showed interest in the topic.

Moving to the supply chain, the agriculture sector is the most involved in CE's initiatives. Circularity is not new in the sector. For a long time, agriculture has been closing the loop of resources, e.g., using animal waste as organic crop fertilizer (Barros et al., 2020). On the contrary, a lack of contribution is reported on the consumption and retail stage. The lack of the first could be explained by the research query of the study, which is focused on the organizational level and does not directly address consumers. The latter's lack is in line with previous literature (Esposito et al., 2020). Nevertheless, interesting insights come out of the analysis. The retail stage could ensure the quality and safety of perishable food products, also reducing the environmental impact of transportation (Kazancoglu et al., 2021). As highlighted by the sample, management operations and store suppliers are critical to reducing waste. In this sense, technological innovations could be adopted to guide store suppliers according to sales forecasts and perishability information. For example, cameras and odour sensors could be employed in supermarkets to collect information and used to predict the deterioration of food products (De Souza et al., 2021). Thus, more studies are needed in retailing stage for the AFS and technology could play a key role in their implementation.

Despite the increased interest in the topic, the lack of a common classification for food streams limits the possibility to develop regulatory measures to exploit food circularity potential (Teigiserova et al., 2020). Classifying processes and practices of the sector is crucial to understanding which strategies could promote the reuse or transformation of food in a sustainable sense. In this case, the classification process and analysis enabled the assessment of sector's maturity in terms of circularity, given the high presence of conventional practices. In detail, a table containing the description of the whole set of CE practices is available in the supplementary material. Circularity is a stable presence in the sector, but its level is still low according to the Rs framework; indeed, conventional practices mainly adopt recovery strategies, especially to produce energy. Nevertheless, a significant portion of such practices employs reduction strategies. According to CE principles, reducing, reusing, or recycling operations should be preferred to recovery ones, to retain the highest value of resources as long as possible (Korhonen et al., 2018). Thus, reducing strategies should be promoted in the sector. An example is the use of manure or crop residues to obtain organic fertilizer, avoiding damage to the soil and the underwater (Kowalski and Makara, 2021; Fernandez-Mena et al., 2020; Novara et al., 2022). Other examples are the use of dripping irrigation and nozzle spray to reduce irrigation water (Novara et al., 2022; de Vasconcelos et al., 2021). Relevant is also food donation; nevertheless, the portion of food redistributed is still limited due to a lack of data regarding food quantity and quality (Amicarelli et al., 2021).

Incrementally innovative practices play another relevant role in the sector's maturity and circularity. Recovery processes are still the most common but reuse operations are considerable. Recovery strategies are dominated by reprocessing processes, directed to energy nutrient and material purposes. While reuse strategies are pursued by optimization and sharing processes. Sharing options have a high potential, especially in rural contexts. It promotes efficient use of resources and interactions between individuals, empowering communities (Rodrigues et al., 2021). Common examples are the exchange of agricultural inputs (Maass and Grundmann, 2016; Fernandez-Mena et al., 2020) or food donation (Rodrigues et al., 2021; de Vasconcelos et al., 2021). In this context, the presence of both technological and socio-organizational innovation is needed. So far, solely the technological dimension has been pursued, leaving small room for socio-organizational change (Potting et al., 2017). The same tendency was encountered in the AFS, where socio-organizational innovations are mainly represented by sharing practices. Nevertheless, the AFS plays a cultural and not solely a nutritional role; thus, it is relevant to support technical change with socio-organization to allow circularity to take root in society.

Lastly, a limited number of practices were classified as radically innovative. According to the literature indeed, innovation in CE involves improvements to existing processes (Homrich et al., 2018). Here, the technological dimension of innovation was favoured, excluding the socio-organizational one. Moreover, all the practices of the subsample are connected to recycling strategies to obtain renewed materials, showing a medium level of circularity. A representative example is given by the first citrus fabric in the world that obtains acetate and silk from citrus waste (Boccia et al., 2021).

Thus, the presence of many conventional practices indicates that CE is already part of the AFS. As the analysis pointed out, rediscovering conventional practices is urgent to improve the integrity and resilience of the geosystems. It is urgent, though, to match such knowledge with incrementally innovative techniques, which showed already a good level of circularity. Enriching conventional practices with technological and socio-organizational innovations following the R framework will allow the sector to exploit the full circularity (Potting et al., 2017).

To promote circularity in the sector is crucial to assess its level of awareness regarding CE. For this reason, content analysis was adopted. It allowed to track the level of conceptualization of CE and the link with other narratives. The analysis evidenced a good level of contextualization, considering that the review analyzed empirical case studies, where the theoretical part is usually limited. Moreover, a small but significant portion of the articles explored the relations between CE and other sustainable constructs (i.e., bioeconomy, industrial ecology, sharing economy), emphasizing the evolutionary nature of CE. Contextualizing and non-contextualizing studies favour recovery strategies, while those studies that stress the evolutionary conception of CE entail more reducing strategies, which entail a higher level of circularity. Nevertheless, the study considers only peer-reviewed contributions; thus, this result is limited to the academic field. Overall, CE is presented as an evolving social construct built upon sedimented layers of different constructs, all contributing to the sustainability agenda (Zucchella and Previtali, 2019). In this sense, some studies have linked CE to IS. Despite a limited number of studies did so, it is still an interesting result, given that IS was not present in the research keywords. Such articles embody a wider perspective, defining case studies involving more than one process. The studies that mention IS emphasize the systemic perspective of CE, namely the capacity to give results on different levels of SD. However, the lack of an environmental organizational perspective limits the possibility of exploiting the synergies of IS in a circular sense. According to some authors (Zucchella and Previtali, 2019) the presence of an “intermediary” is crucial to create a network of stakeholders and, operating from the inside, guiding them towards sustainable business models. Thus, an organizational perspective would improve the presence of IS in the sector.

Finally, the link with SD is mentioned but rarely contextualized. It is perceived in the sample as a long-term goal of circularity, but too wide and vague in the short term, even though a well-known definition of SD exists (Baratsas et al., 2021). One possible explanation for the low contextualization could be the empirical nature of the studies analyzed. Moreover, most of the studies address solely the environmental pillar of SD. Only a few studies combine the environmental pillar with the economic one and no one analyses in detail the social perspective. Examples of practices with positive social implications are donating surplus food to charity (Principato et al., 2019), or promoting occupation (Kowalski and Makara, 2021). The study highlighted the underestimation of the social pillar, already pointed out by the literature (Murray et al., 2017; Ghisellini et al., 2016). Such lack in the sample seems not linked to the methodology adopted by the studies, the only article which directly address the pillar used a quali-quantitative approach, while those who present socially relevant practices show a qualitative or a quantitative nature with no significant trend. On the contrary, the AFS should involve social communities in the transition by promoting bottom-up initiatives that raise awareness over sustainability discourse and stimulate their engagement in circular actions.

5. Conclusions

The present study aimed to provide a systematic and bibliometric analysis of the CE practices in the AFS at the micro and *meso* level. It investigated the context of such practices and prosed a classification to analyse the sector's maturity and circularity. In addition, the awareness of the sector regarding CE and its relations with IS and SD was assessed. The analysis identified 43 scientific articles allowing the collection of 162 practices.

Research interest in CE's is growing and spreading. The sector's maturity has been assessed due to the large presence of conventional practices but with a low level of circularity. On the contrary, incrementally innovative practices show higher levels of circularity. Therefore, it is crucial to couple conventional knowledge with innovative techniques both in technological and socio-organizational terms. The sector already proved its awareness regarding CE. On the contrary, the links with IS are not fully exploited, while SD is considered the long-term objective of CE but is still a vague concept. Especially its social side is underestimated in the sector. This research enables to capture the characteristics of circularity in the AFS and reporting examples of best practices. This allows us to guide practitioners interested in applying CE in the sector and academics to identify possible improvements.

However, some limitations are present; for example, regarding the research methods adopted, which may have excluded some potentially relevant studies. Moreover, the relevant presence of conventional practices was considered a proxy of the sector's maturity; nevertheless, it may also be due to its minor structural elasticity to innovation and this aspect could inspire future research. Thus, future research is planned to guide companies of the AFS towards circularity, understanding how they assess circularity and sustainability by providing a selected case study analysis. Further future investigation should also integrate the macro scale into the analysis, exploring the circular practices implemented at city, region or country scales in the sector.

Finally, it is hoped that the present SLR can advise future research, contributing to the diffusion of CE practices in the AFS. Relevant lacks have been identified in this study, namely the limited role played by incremental innovativeness and the lack of social perspective. To promote social sensibility, the sector should boost community engagement through sensibilization campaigns or incentives to stimulate circular and sustainable actions. This would guide, on the one hand, communities towards awareness and smart initiatives and, on the other, the policymakers in designing their policy interventions on communities' ideas and needs.

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

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2023.107079.

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1.1 Theoretical Overview

This section displays the reasoning behind the realization of the present SLR, emphasizing the strengths and limitations of existing literature on this topic.

1.1.1 Circular Economy and Industrial Symbiosis: a way towards Sustainability

In the last decade, the CE concept has achieved increased consideration to operationalize sustainability (Kirhhner et al., 2017-Ghisellini et al., 2016). CE spread as policy intervention started in China (PRC, 2008); afterwards, several institutions promoted CE, like the European Commission (EC), which introduced the "Closing the Loop: An EU Action plan for the Circular Economy Package" (EC, 2015) in 2015.CE principles are well-identified by the R frameworks, which describe how to apply circularity practically and are used by academia and practitioners (Kirhhner et al., 2017). Prominent is the configuration of the 4Rs (reduce, reuse, recycle and recover) used in the Waste Framework Directive by the EU (EC, 2008) and the 9Rs (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover) more nuanced and specific (Potting et al., 2017). Circularity may operate at different levels, macro (e.g., cities, regions, or nations), meso (e.g., eco-industrial parks, industrial symbiosis networks), or micro (e.g., companies or products) (Ghisellini et al., 2016). As stressed earlier, at the meso level it may configure as an example of Industrial Symbiosis (IS). IS favours resource efficiency while reducing waste generation through energy, materials, and by-products exchanges. It offers a concrete approach to closing the loop of resources, turning the waste produced by industry into feedstock for another one (Domenech et al., 2019). The connection between CE and IS is not new. In China Eco-Industrial parks initiatives have been encouraged since 2008 to reuse of waste as resources. Circular thinking requires co-creation spaces and processes that leverage on collaborative relations among companies and actors thus, to exploit the circularity inter and intra company synergies should be emphasized. CE and IS are sustainable narratives, namely approaches capable of addressing sustainability challenges by pursuing different Sustainable Development Goals (SDGs), the global agenda promoted by the United Nations. However, their relationship with sustainability is puzzling. As already mentioned, CE is characterized by trade-offs and rebound effects, which make the connection to sustainability unclear. Eco-efficiency does not directly imply sustainability, and it is necessary to measure the net global sustainability of practices before claiming them as circular and sustainable (Korhonen et al., 2018). Even though they share several principles, they embrace different goals and perspectives; sustainability is grounded on 3 pillars: environmental quality, economic prosperity, and social equity, considered equally important to reach SD, while CE is resource-focused, aimed at inputs and waste reduction to eliminate the net effect on the environment (Geissdoerfer et al., 2017). Sustainability considers the social perspective regarding well-being and human rights, giving clear emphasis on inter and intra-generational equity and social justice.

Besides, the vagueness of the relationship may result in greenwashing phenomena, where company practices claimed as highly sustainable hide questionable outcomes from an environmental, societal, or economic perspective (Opferkuch et al., 2021). Thus, it is relevant to understand how circularity is perceived and implemented to evaluate its capacity to address sustainability challenges.

1.1.2 Circularity in the Agri-food system

Circularity has ancient roots in the AFS. The sector offers numerous possibilities to give residues and waste new life, moving from scraps to resources in the same or a different value chain (Zarbà et al., 2021).

At the same time, the lack of a common definition of food waste limits the possibility of defining appropriate classification methods for distinguishing the various waste streams (Teigiserova et al., 2020). This hampers the possibility of developing appropriate regulatory measures to exploit food potential, e.g., in the European legislation, there are no legislative interventions directly targeted for the AFS (Zarbà et al., 2021). Thus, classifying AFS processes and practices is important to understand how to valorise their potential reuse or transformation. There are different examples of categorization models for the AFS in the literature. Papargyropoulou et al. (2014), in their "Food waste hierarchy" made a clear distinction between food loss and waste, emphasizing the importance of prevention and reuse options, since they allow for reducing the negative social and ethical implications, limiting the depletion of natural resources (Ciccullo et al., 2021).

On the other hand, Garcia-Garcia et al. (2017), expanded end-of life strategies, including processes like the extraction of compounds of interest among the recycling treatments, but not considering the distinctions among surplus, waste and loss. Other food waste frameworks are provided by the Moerman's Ladder (Rood et al., 2017), employed for preventing food waste, or the Food waste management hierarchy by Vandermeersch et al. (2014), which focused on the prevention of food waste and loss, without considering the surplus food. Despite the numerous contributions in this sense, the challenge to establish a standardized hierarchical order for the sector is still open and needs to be filled. Detecting the goals of the practices implemented in the sector enables one to comprehend which strategies are or could be implemented. This gives the chance to compare the different scenarios and promote the most circular one. The most advisable approach for the sector could be the one that blends tradition with innovation.

Traditional agri-food techniques offer valuable insights into facing the sector's challenges, and promoting a healthy, secure, and resilient agri-food system (Altieri and Nicholls, 2013). Wheatear, modern agriculture has proved to be focused solely on short-term productivity, overlooking long-term resilience (Sing and Sing, 2017). According to Dossa et al. (2020), the sector, does not need to be reshaped since it is already marked by circularity. Indeed, several practices commonly spread in farming can already be defined as circular, such as the "no-tillage agriculture", which limits the soil erosion usually caused by mechanical tillage. On the other hand, innovation could be analysed in technological and socio-institutional sense. According to Potting et al. (2017), the first is less relevant in CE, while the latter entails the transformative power to spread circular thinking.

On the contrary, D'Amato (2021) argues that nowadays the transformation proposed by developed countries in terms of CE lies in technological improvement. Technology indeed plays a mediating role that enables to retain resources and value as possible. Assessing the innovativeness of the sector practices is relevant to understand what kind of knowledge and tools could be employed, exploiting the synergies between traditional knowledge and innovative know-how. Circularity needs tailored solutions capable addressing a specific territory's contextual issues, e.g., its socio-economical, demographical, or cultural characteristics (D'Amato, 2021). This is particularly true for the food system, given the peculiarities of each territory. In this sense, traditional knowledge and know-how enable to identify possible leveraging factors based on the intrinsic characteristics of a territory, which, when combined with technological tools, allows to match the type of intervention with the available resources of a specific location. Thus, it is relevant to question if and how the traditional background, enriched with innovative technical knowledge can generate a new concept of innovation, which is globally relevant, but also cite specific.

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1.2 Supplementary materials

Table S1-Overview of the bibliometric information of the sample

Author	Title	Year	Source title
Suckling J., Druckman A., Small R., Cecelja F., Bussemaker M.	Supply chain optimization and analysis of Hermetia illucens (black soldier fly) bioconversion of surplus foodstuffs	2021	Journal of Cleaner Production
Cortés A., Esteve-Llorens X., González-García S., Moreira M.T., Feijoo G.	Multi-product strategy to enhance the environmental profile of the canning industry towards circular economy	2021	Science of the Total Environment
Cardoso R.V.C., Fernandes Â., Barreira J.C.M., Abreu R.M.V., Mandim F., Gonzaléz-Paramás A.M., Ferreira I.C.F.R., Barros L.	A Case Study on Surplus Mushrooms Production: Extraction and Recovery of Vitamin D-2	2021	Agriculture (Switzerland)
Ncube A., Fiorentino G., Colella M., Ulgiati S.	Upgrading wineries to biorefineries within a Circular Economy perspective: An Italian case study	2021	Science of the Total Environment
Rodrigues T.C., Leitão F.O., Thomé K.M., Cappellesso G.	Sharing economy practices in agri-food settlements: Integration of resources, interdependence and interdefinition	2021	Journal of Cleaner Production
Dorr E., Koegler M., Gabrielle B., Aubry C.	Life cycle assessment of a circular, urban mushroom farm	2021	Journal of Cleaner Production
Kowalski Z., Makara A.	The circular economy model used in the polish agro-food consortium: A case study	2021	Journal of Cleaner Production
Rollini M., Musatti A., Cavicchioli D., Bussini D., Farris S., Rovera C., Romano D., De Benedetti S., Barbiroli A.	From cheese whey permeate to Sakacin-A/bacterial cellulose nanocrystal conjugates for antimicrobial food packaging applications: a circular economy case study	2020	Scientific Reports
Patrizi N., Bruno M., Saladini F., Parisi M.L., Pulselli R.M., Bjerre A.B., Bastianoni S.	Sustainability Assessment of Biorefinery Systems Based on Two Food Residues in Africa	2020	Frontiers in Sustainable Food Systems
Manríquez-Altamirano A., Sierra-Pérez J., Muñoz P., Gabarrell X.	Analysis of urban agriculture solid waste in the frame of circular economy: Case study of tomato crop in integrated rooftop greenhouse	2020	Science of the Total Environment
Overturf E., Ravasio N., Zaccheria F., Tonin C., Patrucco A., Bertini F., Canetti M., Avramidou K., Speranza G., Bavaro T., Ubiali D.	Towards a more sustainable circular bioeconomy. Innovative approaches to rice residue valorization: The RiceRes case study	2020	Bioresource Technology Reports
Keng Z.X., Chong S., Ng C.G., Ridzuan N.I., Hanson S., Pan G.-T., Lau P.L., Supramaniam C.V., Singh A., Chin C.F., Lam H.L.	Community-scale composting for food waste: A life-cycle assessment-supported case study	2020	Journal of Cleaner Production

Author	Title	Year	Source title
Sellitto M.A., Almeida F.A.	Strategies for value recovery from industrial waste: case studies of six industries from Brazil…?	2020	Benchmarking
Marrucci L., Marchi M., Daddi T.	Improving the carbon footprint of food and packaging waste management in a supermarket of the Italian retail sector	2020	Waste Management
Lucchetti M.G., Paolotti L., Rocchi L., Boggia A.	The Role of Environmental Evaluation within Circular Economy: An Application of Life Cycle Assessment (LCA) Method in the Detergents Sector	2019	Environmental and Climate Technologies
Laso J., Margallo M., García-Herrero I., Fullana P., Bala A., Gazulla C., Polettini A., Kahhat R., Vázquez-Rowe I., Irabien A., Aldaco R.	Combined application of Life Cycle Assessment and linear programming to evaluate food waste-to-food strategies: Seeking for answers in the nexus approach	2018	Waste Management
Liu H., Ou X., Yuan J., Yan X.	Experience of producing natural gas from corn straw in China	2018	Resources, Conservation and Recycling
Rentizelas A., Shpakova A., Mašek O.	Designing an optimised supply network for sustainable conversion of waste agricultural plastics into higher value products	2018	Journal of Cleaner Production
Fuldauer L.I., Parker B.M., Yaman R., Borrion A.	Managing anaerobic digestate from food waste in the urban environment: Evaluating the feasibility from an interdisciplinary perspective	2018	Journal of Cleaner Production
Santagata R., Ripa M., Ulgiati S.	An environmental assessment of electricity production from slaughterhouse residues. Linking urban, industrial and waste management systems	2017	Applied Energy
Chen L., Cong R.-G., Shu B., Mi Z.-F.	A sustainable biogas model in China: The case study of Beijing Deqingyuan biogas project	2017	Renewable and Sustainable Energy Reviews
Maaß O., Grundmann P.	Added-value from linking the value chains of wastewater treatment, crop production and bioenergy production: A case study on reusing wastewater and sludge in crop production in Braunschweig (Germany)	2016	Resources, Conservation and Recycling
Strazza C., Magrassi F., Gallo M., Del Borghi A.	Life Cycle Assessment from food to food: A case study of circular economy from cruise ships to aquaculture IS	2015	Sustainable Production and Consumption
Brenes-Peralta, L; Jimenez-Morales, ME; Campos-	Decision-Making Process in the Circular Economy: A Case Study on University Food	2020	Energies

Author	Title	Year	Source title
Rodriguez, R; De Menna, F; Vittuari, M	Waste-to-Energy Actions in Latin America		
Zabaniotou, A; Rovas, D; Libutti, A; Monteleone, M	Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis-biochar based system integrated in an olive farm in symbiosis with an olive mill	2015	Environmental Development
Zhu, Q; Jia, RA; Lin, XH	Building sustainable circular agriculture in China: economic viability and entrepreneurship	2019	Managment Decision
de Sousa, MH; da Silva, ASF; Correia, RC; Leite, NP; Bueno, CEG; Pinheiro, RLD; de Santana, JS; da Silva, JL; Sales, AT; de Souza, CC; Aquino, KAD; de Souza, RB; Pinheiro, IO; Henriquez, JR; Schuler, ARP; Sampaio, EVDB; Dutra, ED; Menezes, RMSC	Valorizing municipal organic waste to produce biodiesel, biogas, organic fertilizer, and value-added chemicals: an integrated biorefinery approach	2021	Biomass Conversion and Biorefinery
Yu, F; Han, F; Cui, ZJ	Evolution of industrial symbiosis in an eco-industrial park in China (IS)	2015	Journal of Cleaner Production
Zucchella, A; Previtali, P	Circular business models for sustainable development: A waste is food restorative ecosystem	2019	Business Strategy and the Environment
Kerdlap P., Low J.S.C., Tan D.Z.L., Yeo Z., Ramakrishna S.	M3-IS-LCA: A Methodology for Multi-level Life Cycle Environmental Performance Evaluation of Industrial Symbiosis Networks	2020	Resources, Conservation and Recycling
Costa, M; Buono, A; Caputo, C; Carotenuto, A; Cirillo, D; Costagliola, MA; Di Blasio, G; La Villetta, M; Macaluso, A; Martoriello, G; Massarotti, N; Mauro, A; Migliaccio, M; Mulone, V; Murena, F; Piazzullo, D; Prati, MV; Rocco, V; Stasi, A; Vanoli, L; Cinocca, A; Di Battista, D; De Vita, A	The INNOVARE Project: Innovative Plants for Distributed Poly-Generation by Residual Biomass	2020	Energies
Boccia F., Di Pietro B., Covino D.	Food waste and environmental-sustainable innovation: A scenario for the Italian citrus market	2021	Quality - Access to Success
Kılkış Ş., Kılkış B.	Integrated circular economy and education model to address aspects of an energy-water-food nexus in a dairy facility and local contexts	2017	Journal of Cleaner Production
Fernandez-Mena H., MacDonald G.K., Pellerin S., Nesme T.	Co-benefits and Trade-Offs From Agro-Food System Redesign for Circularity: A Case Study With the FAN Agent-Based Model	2020	Frontiers in Sustainable Food Systems

Author	Title	Year	Source title
Principato L., Ruini L., Guidi M., Secondi L.	Adopting the circular economy approach on food loss and waste: The case of Italian pasta production	2019	Resources, Conservation and Recycling
Baratsas S.G., Pistikopoulos E.N., Avraamidou S.	A systems engineering framework for the optimization of food supply chains under circular economy considerations	2021	Science of the Total Environment
Zuin, VG; Ramin, LZ; Segatto, ML; Stahl, AM; Zanotti, K; Forim, MR; da Silva, MFDF; Fernandes, JB	To separate or not to separate: what is necessary and enough for a green and sustainable extraction of bioactive compounds from Brazilian citrus waste	2021	Pure and Applied Chemistry
Jiménez-Benítez A., Ferrer F.J., Greses S., Ruiz-Martínez A., Fatone F., Eusebi A.L., Mondéjar N., Ferrer J., Seco A.	AnMBR, reclaimed water and fertigation: Two case studies in Italy and Spain to assess economic and technological feasibility and CO2 emissions within the EU Innovation Deal initiative	2020	Journal of Cleaner Production
Michele de Souza, Giancarlo Medeiros Pereira, Ana Beatriz Lopes de Sousa Jabbour ,Charbel Jose Chiappetta Jabbour, Luiz Reni Trento a, Miriam Borchardt a, Leandro Zvirtes	A digitally enabled circular economy for mitigating food waste: Understanding innovative marketing strategies in the context of an emerging economy	2021	Technological forecasting and social change
Kafel P., Nowicki P., Balon U.	Microplastics risk at the interface of circular economy	2021	Business: Theory and Practice
de Vasconcelos D.C., Viana F.L.E., de Souza A.L.	Circular Economy and Sustainability in the Fresh Fruit Supply Chain: A Study across Brazil and the UK	2021	Latin American Business Review
Lima A., Abreu T., Figueiredo S.	Water and wastewater optimization in a food processing industry using water pinch technology	2021	Sustainable Water Resources Management
Novara, A., Sampino, S., Paternò, F., Keesstra, S.	Climate Smart Regenerative Agriculture to Produce Sustainable Beauty Products: The Case Study of Snail Secretion Filtrate (LX360®)	2022	Sustainability (Switzerland)

Table S2 Summary of the CE practices identified in the sample

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
1	Suckling et al. (2021)	Supply chain O and analysis of Hermetia illucens (black soldier fly) bioconversion of surplus foodstuffs	Reprocessing	Animal feed	R3	Incrementally Innovative	T	UK	Agriculture	Processing
2	Cortes et al. (2021)	Multi-product strategy to enhance the environmental profile of the canning industry towards circular economy	Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Spain	Fish breeding	Whole SC
3	Cortes et al. (2021)		Optimization of the prodution process	Technologies	R1	Conventional	NA	Spain	Fish breeding	Whole SC
4	Cortes et al. (2021)		Optimization of the prodution process	Technologies	R1	Conventional	NA	Spain	Fish breeding	Whole SC
5	Cortes et al. (2021)		Reprocessing	Human food	R2	Conventional	NA	Spain	Fish breeding	Whole SC
6	Cortes et al. (2021)		Reprocessing	Animal feed	R3	Conventional	NA	Spain	Fish breeding	Whole SC
7	Cardoso et al. (2020)	A Case Study on Surplus Mushrooms Production: Extraction and R4y of Vitamin D-2	Reprocessing	Nutrients	R3	Incrementally Innovative	T	Portugal	Agriculture	Production
8	Ncube et al., (2021)	Upgrading wineries to biorefineries within a Circular Economy perspective: An Italian case study	Reprocessing	Materials	R3	Incrementally Innovative	T	Italy	Agriculture	Processing
9	Ncube et al., (2021)		Reprocessing	Materials	R3	Incrementally Innovative	T	Italy	Agriculture	Processing
10	Ncube et al., (2021)		Reprocessing	Energy	R4	Incrementally Innovative	T	Italy	Agriculture	Processing
11	Ncube et al., (2021)		Reprocessing	Energy	R4	Incrementally Innovative	T	Italy	Agriculture	Processing
12	Ncube et al., (2021)		Reprocessing	Materials	R3	Incrementally Innovative	T	Italy	Agriculture	Processing
13	Ncube et al., (2021)		Optimization of the prodution process	Materials in inputs	R1	Incrementally Innovative	S-O	Italy	Agriculture	Processing

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
14	Ncube et al., (2021)		Reprocessing	Energy	R4	Incrementally Innovative	T	Italy	Agriculture	Processing
15	Rodrigues et al. (2021),	Sharing economy practices in agri-food settlements: Integration of resources, interdependence and interdefinition	Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
16	Rodrigues et al. (2021),		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
17	Rodrigues et al. (2021),		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
18	Rodrigues et al. (2021),		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
19	Rodrigues et al. (2021),		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
20	Rodrigues et al. (2021),		Sharing of resources	Intangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
21	Rodrigues et al. (2021),		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
22	Rodrigues et al. (2021),		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
23	Rodrigues et al. (2021),		Sharing of resources	Intangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
24	Rodrigues et al. (2021),		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
25	Rodrigues et al. (2021),		Sharing of resources	Intangibles	R1	Incrementally Innovative	S-O	Brazil	Agriculture	Whole SC
26	Dorr et al. (2021)	Life cycle assessment of a circular, urban mushroom farm	Reprocessing	Nutrients	R4	Incrementally Innovative	T	France	Agriculture	Production
27	Dorr et al. (2021)		Reprocessing	Nutrients	R4	Incrementally Innovative	T	France	Agriculture	Production
28	Kowalski and Makara (2021)	The circular economy model used in the polish agro-food consortium: A case study	Reprocessing	Pet food	R3	Incrementally Innovative	T	Poland	Livestock	Whole SC

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
29	Kowalski and Makara (2021)		Reprocessing	Energy	R4	Incrementally Innovative	T	Poland	Livestock	Whole SC
30	Kowalski and Makara (2021)		Reprocessing	Energy	R4	Incrementally Innovative	T	Poland	Livestock	Whole SC
31	Kowalski and Makara (2021)		Reprocessing	Materials	R3	Incrementally Innovative	T	Poland	Livestock	Whole SC
32	Kowalski and Makara (2021)		Reprocessing	Energy	R4	Conventional	NA	Poland	Livestock	Whole SC
33	Kowalski and Makara (2021)		Reprocessing	Water	R4	Conventional	NA	Poland	Livestock	Whole SC
34	Kowalski and Makara (2021)		Reprocessing	Pet food	R3	Conventional	NA	Poland	Livestock	Whole SC
35	Kowalski and Makara (2021)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Poland	Livestock	Whole SC
36	Rollini et al (2020) ex musatti	From cheese whey permeate to Sakacin-A/bacterial cellulose nanocrystal conjugates for antimicrobial food packaging applications: a circular economy case study	Reprocessing	Materials	R3	Radically Innovative	T	Italy	Dairy	Processing
37	Patrizi et al. (2020)	Sustainability Assessment of Biorefinery Systems Based on Two Food Residues in Africa	Reprocessing	Energy	R4	Conventional	NA	Ghana	Agriculture	Processing
38	Patrizi et al. (2020)		Reprocessing	Energy	R4	Incrementally Innovative	T	Ghana	Agriculture	Processing

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
39	Manríquez-Altamirano et al. (2020)	Analysis of urban agriculture solid waste in the frame of circular economy: Case study of tomato crop in integrated rooftop greenhouse	Reprocessing	Nutrients	R4	Incrementally Innovative	T	Spain	Agriculture	Production
40	Overturf et al. (2020)	Towards a more sustainable circular bioeconomy. Innovative approaches to rice residue valorization: The RiceRes case study	Reprocessing	Materials	R3	Incrementally Innovative	T	Italy	Agriculture	Processing
41	Overturf et al. (2020)		Reprocessing	Materials	R3	Radically Innovative	T	Italy	Agriculture	Processing
42	Overturf et al. (2020)		Reprocessing	Materials	R3	Incrementally Innovative	T	Italy	Agriculture	Processing
43	Overturf et al. (2020)		Reprocessing	Materials	R3	Incrementally Innovative	T	Italy	Agriculture	Processing
44	Keng et al. (2020)	Community-scale composting for food waste: A life-cycle assessment-supported case study	Reprocessing	Nutrients	R4	Conventional	NA	Malaisya	Agriculture	End of life
45	Sellitto et al. (2019)	Strategies for value R4y from industrial waste: case studies of six industries from Brazil	Optimization of the prodution process	Materials in inputs	R2	Conventional	NA	Brazil	Various	Processing
46	Sellitto et al. (2019)		Reprocessing	Animal feed	R3	Conventional	NA	Brazil	Various	Processing
47	Sellitto et al. (2019)		Reprocessing	Energy	R4	Conventional	NA	Brazil	Various	Processing
48	Sellitto et al. (2019)		Reprocessing	Nutrients	R4	Conventional	NA	Brazil	Various	Processing
49	Marrucci et al. (2020)	Improving the carbon footprint of food and packaging waste management in a supermarket of the Italian retail sector	Incineration&Landfilling	Without biogas	D	Conventional	NA	Italy	Various	Retail
50	Marrucci et al. (2020)		Reprocessing	Energy	R4	Conventional	NA	Italy	Various	Retail
51	Marrucci et al. (2020)		Reprocessing	Nutrients	R4	Conventional	NA	Italy	Various	Retail

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
52	Marrucci et al. (2020)		Reprocessing	Energy	R4	Conventional	NA	Italy	Various	Retail
53	Marrucci et al. (2020)		Reprocessing	Materials	R3	Conventional	NA	Italy	Various	Retail
54	Marrucci et al. (2020)		Incineration&Landfilling	Without biogas	D	Conventional	NA	Italy	Various	Retail
55	Marrucci et al. (2020)		Incineration&Landfilling	Without biogas	D	Conventional	NA	Italy	Various	Retail
56	Marrucci et al. (2020)		Reprocessing	Energy	R4	Conventional	NA	Italy	Various	Retail
57	Marrucci et al. (2020)		Reprocessing	Energy	R4	Conventional	NA	Italy	Various	Retail
58	Lucchetti et al. (2019)	The Role of Environmental Evaluation within Circular Economy: An Application of Life Cycle Assessment (LCA) Method in the Detergents Sector	Reprocessing	Materials	R3	Incrementally Innovative	T	Italy	Various	Consumptio n
59	Laso et al. (2018)	Combined application of Life Cycle Assessment and linear programming to evaluate food waste-to-food strategies: Seeking for answers in the nexus approach	Incineration&Landfilling	With biogas	R4	Conventional	NA	Spain	Fish breeding	Processing
60	Laso et al. (2018)		Incineration&Landfilling	With biogas	R4	Conventional	NA	Spain	Fish breeding	Processing
61	Laso et al. (2018)		Reprocessing	Animal feed	R3	Conventional	NA	Spain	Fish breeding	Processing
62	Liu et al. (2018)	Experience of producing natural gas from corn straw in China	Reprocessing	Energy	R4	Conventional	NA	China	Agriculture	Production
63	Liu et al. (2018)		Reprocessing	Nutrients	R4	Conventional	NA	China	Agriculture	Production
64	Rentizelas et al. (2018)	Designing an optimised supply network for	Reprocessing	Materials	R4	Incrementally Innovative	T	UK	Agriculture	End of life

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
65	Rentizelas et al. (2018)	sustainable conversion of waste agricultural plastics into higher value products	Reprocessing	Energy	R4	Incrementally Innovative	T	UK	Agriculture	End of life
66	Rentizelas et al. (2018)		Reprocessing	Energy	R4	Incrementally Innovative	T	UK	Agriculture	End of life
67	Fuldauer et al. (2018)	Managing anaerobic digestate from food waste in the urban environment: Evaluating the feasibility from an interdisciplinary perspective	Reprocessing	Nutrients	R4	Incrementally Innovative	T	UK	Agriculture	End of life
68	Fuldauer et al. (2018)		Reprocessing	Nutrients	R4	Incrementally Innovative	T	UK	Agriculture	End of life
69	Santagata et al. (2017)	An environmental assessment of electricity production from slaughterhouse residues. Linking urban, industrial and waste management systems	Reprocessing	Pet food	R3	Conventional	NA	Italy	Livestock	Processing
70	Santagata et al. (2017)		Reprocessing	Energy	R4	Incrementally Innovative	T	Italy	Livestock	Processing
71	Chen et al. (2017)	A sustainable biogas model in China: The case study of Beijing Deqingyuan biogas project	Reprocessing	Energy	R4	Incrementally Innovative	T	China	Livestock	Production
72	Chen et al. (2017)		Reprocessing	Nutrients	R4	Incrementally Innovative	T	China	Livestock	Production
73	Maass and Grundmann (2016)	Added-value from linking the value chains of wastewater treatment, crop production and bioenergy production: A case study on reusing wastewater and sludge in crop production in Braunschweig (Germany)	Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Germany	Water	End of life
74	Maass and Grundmann (2016)		Reprocessing	Water	R2	Conventional	NA	Germany	Water	End of life
75	Maass and Grundmann (2016)		Reprocessing	Energy	R4	Conventional	NA	Germany	Water	End of life
76	Maass and Grundmann (2016)		Reprocessing	Water	R2	Conventional	NA	Germany	Water	End of life

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
77	Strazza et al. (2015)	Life Cycle Assessment from food to food: A case study of circular economy from cruise ships to aquaculture	Reprocessing	Animal feed	R3	Radically Innovative	T	UK	Various	Consumption
78	Brenes-Peralta et al. (2020)	Decision-Making Process in the Circular Economy: A Case Study on University Food Waste-to-Energy Actions in Latin America	Reprocessing	Energy	R4	Conventional	NA	Costa Rica	Agriculture	Consumption
79	Brenes-Peralta et al. (2020)		Reprocessing	Nutrients	R4	Conventional	NA	Costa Rica	Agriculture	Consumption
80	Brenes-Peralta et al. (2020)		Reprocessing	Nutrients	R4	Conventional	NA	Costa Rica	Agriculture	Consumption
81	Zabaniotou et al. (2015)	Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis-biochar based system integrated in an olive farm in symbiosis with an olive mill	Reprocessing	Energy	R4	Incrementally Innovative	T	Italy	Agriculture	Processing
82	Zabaniotou et al. (2015)		Optimization of the prodution process	Energy in input	R1	Incrementally Innovative	T	Italy	Agriculture	Processing
83	Zabaniotou et al. (2015)		Reprocessing	Energy	R4	Incrementally Innovative	T	Italy	Agriculture	Processing
84	Zabaniotou et al. (2015)		Reprocessing	Nutrients	R4	Conventional	NA	Italy	Agriculture	Processing
85	Zhu et al. (2019)	Building sustainable circular agriculture in China: economic viability and entrepreneurship	Reprocessing	Energy	R4	Conventional	NA	China	Livestock	Production
86	Zhu et al. (2019)		Reprocessing	Nutrients	R4	Conventional	NA	China	Livestock	Production
87	De Sousa et al. (2021)	Valorizing municipal organic waste to produce biodiesel, biogas, organic fertilizer, and value-added chemicals: an integrated biorefinery approach	Reprocessing	Energy	R4	Conventional	NA	Brazil	Various	End of life
88	De Sousa et al. (2021)		Reprocessing	Energy	R4	Conventional	NA	Brazil	Various	End of life
89	De Sousa et al. (2021)		Reprocessing	Nutrients	R4	Conventional	NA	Brazil	Various	End of life

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
90	Yu et al. (2015)	Evolution of industrial symbiosis in an eco-industrial park in China	Sharing of resources	Tangibles	R1	Incrementally Innovative	T	China	Various	Processing
91	Yu et al. (2015)		Optimization of the prodution process	Materials in inputs	R1	Incrementally Innovative	T	China	Various	Processing
92	Yu et al. (2015)		Reprocessing	Nutrients	R3	Incrementally Innovative	T	China	Various	Processing
93	Yu et al. (2015)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	China	Various	Processing
94	Yu et al. (2015)		Reprocessing	Materials	R3	Conventional	NA	China	Various	Processing
95	Yu et al. (2015)		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	China	Various	Processing
96	Yu et al. (2015)		Reprocessing	Nutrients	R1	Incrementally Innovative	T	China	Various	Processing
97	Yu et al. (2015)		Optimization of the prodution process	Materials in inputs	R1	Incrementally Innovative	T	China	Various	Processing
98	Zucchella and Previtali (2019)	Circular business models for sustainable development: A waste is food restorative ecosystem	Reprocessing	Nutrients	R4	Incrementally Innovative	T	Italy	Agriculture	End of life
99	Kerdlap et al. (2020)	M3-IS-LCA: A Methodology for Multi-level Life Cycle Environmental Performance Evaluation of Industrial Symbiosis Networks	Reprocessing	Energy	R4	Conventional	NA	Singapore	Various	End of life
100	Kerdlap et al. (2020)		Reprocessing	Nutrients	R4	Conventional	NA	Singapore	Various	End of life
101	Kerdlap et al. (2020)		Reprocessing	Energy	R4	Conventional	NA	Singapore	Various	End of life
102	Kerdlap et al. (2020)		Reprocessing	Energy	R4	Conventional	NA	Singapore	Various	End of life
103	Kerdlap et al. (2020)		Reprocessing	Animal feed	R3	Conventional	NA	Singapore	Various	End of life
104	Costa et al. (2020)	The INNOVARE Project: Innovative Plants for	Reprocessing	Energy	R4	Incrementally Innovative	T	Italy	Various	End of life

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
		Distributed Poly-Generation by Residual Biomass								
105	Boccia et al. (2021)	Food waste and environmental-sustainable innovation: A scenario for the Italian citrus market	Reprocessing	Energy	R4	Conventional	NA	Italy	Agriculture	Production
106	Boccia et al. (2021)		Reprocessing	Nutrients	R4	Conventional	NA	Italy	Agriculture	Production
107	Boccia et al. (2021)		Reprocessing	Materials	R3	Radically Innovative	T	Italy	Agriculture	Production
108	Boccia et al. (2021)		Reprocessing	Materials	R3	Radically Innovative	T	Italy	Agriculture	Production
109	Boccia et al. (2021)		Reprocessing	Energy	R4	Conventional	NA	Italy	Agriculture	Production
110	Kılkış and Kılkış (2017)	Integrated circular economy and education model to address aspects of an energy-water-food nexus in a dairy facility and local contexts	Reprocessing	Nutrients	R4	Conventional	NA	Turkey	Dairy	Processing
111	Kılkış and Kılkış (2017)		Reprocessing	Energy	R4	Conventional	NA	Turkey	Dairy	Processing
112	Kılkış and Kılkış (2017)		Reprocessing	Energy	R4	Incrementally Innovative	T	Turkey	Dairy	Processing
113	Kılkış and Kılkış (2017)		Optimization of the prodution process	Energy in input	R1	Incrementally Innovative	T	Turkey	Dairy	Processing
114	Kılkış and Kılkış (2017)		Reprocessing	Energy	R4	Incrementally Innovative	T	Turkey	Dairy	Processing
115	Kılkış and Kılkış (2017)		Reprocessing	Energy	R4	Incrementally Innovative	T	Turkey	Dairy	Processing
116	Kılkış and Kılkış (2017)		Reprocessing	Energy	R4	Conventional	NA	Turkey	Dairy	Processing
117	Kılkış and Kılkış (2017)		Reprocessing	Energy	R4	Conventional	NA	Turkey	Dairy	Processing
118	Fernandez-Mena et al. (2020)	Co-benefits and Trade-Offs From Agro-Food System Redesign for Circularity: A	Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	France	Various	Production

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
119	Fernandez-Mena et al. (2020)	Case Study With the FAN Agent-Based Model	Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	France	Various	Production
120	Fernandez-Mena et al. (2020)		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	France	Various	Production
121	Fernandez-Mena et al. (2020)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	France	Various	Production
122	Fernandez-Mena et al. (2020)		Reprocessing	Energy	R4	Conventional	NA	France	Various	Production
123	Fernandez-Mena et al. (2020)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	France	Various	Production
124	Fernandez-Mena et al. (2020)		Sharing of resources	Tangibles	R1	Conventional	NA	France	Various	Production
125	Principato et al. (2019)	Adopting the circular economy approach on food loss and waste: The case of Italian pasta production	Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Italy	Agriculture	Whole SC
126	Principato et al. (2019)		Reprocessing	Animal feed	R2	Conventional	NA	Italy	Agriculture	Whole SC
127	Principato et al. (2019)		Reprocessing	Energy	R4	Conventional	NA	Italy	Agriculture	Whole SC
128	Principato et al. (2019)		Incineration&Landfilling	Without biogas	D	Conventional	NA	Italy	Agriculture	Whole SC
129	Principato et al. (2019)		Sharing of resources	Tangibles	R1	Conventional	NA	Italy	Agriculture	Whole SC
130	Principato et al. (2019)		Reprocessing	Nutrients	R4	Conventional	NA	Italy	Agriculture	Whole SC
131	Baratsas et al. (2021)	A systems engineering framework for the O of food	Reprocessing	Energy	R4	Incrementally Innovative	T	US	Agriculture	Whole SC

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
132	Baratsas et al. (2021)	supply chains under circular economy considerations (info about the product,not the process-metioning the by-product used as inputs)	Reprocessing	Energy	R4	Incrementally Innovative	T	US	Agriculture	Whole SC
133	Baratsas et al. (2021)		Reprocessing	Energy	R4	Incrementally Innovative	T	US	Agriculture	Whole SC
134	Zuin et al. (2021)	To separate or not to separate: what is necessary and enough for a green and sustainable extraction of bioactive compounds from Brazilian citrus waste	Reprocessing	Nutrients	R3	Incrementally Innovative	T	Brazil	Agriculture	Production
135	Zuin et al. (2021)		Reprocessing	Nutrients	R3	Incrementally Innovative	T	Brazil	Agriculture	Production
136	Zuin et al. (2021)		Reprocessing	Nutrients	R3	Incrementally Innovative	T	Brazil	Agriculture	Production
137	Jiménez-Benítez et al. (2020)	AnMBR, reclaimed water and fertigation: Two case studies in Italy and Spain to assess economic and technological feasibility and CO2 emissions within the EU Innovation Deal initiative.	Reprocessing	Water	R4	Conventional	NA	Italy/Spain	Water	End of life
138	Jiménez-Benítez et al. (2020)		Reprocessing	Water	R4	Incrementally Innovative	T	Italy/Spain	Water	End of life
139	Jiménez-Benítez et al. (2020)		Reprocessing	Water	R4	Incrementally Innovative	T	Italy/Spain	Water	End of life
140	Jiménez-Benítez et al. (2020)		Reprocessing	Water	R4	Conventional	NA	Italy/Spain	Water	End of life
141	Jiménez-Benítez et al. (2020)		Reprocessing	Water	R4	Incrementally Innovative	S-O	Italy/Spain	Water	End of life
142	Jiménez-Benítez et al. (2020)		Reprocessing	Water	R4	Conventional	NA	Italy/Spain	Water	End of life
143	De Souza et al. (2021)	A digitally enabled circular economy for mitigating food	Optimization of the prodution process	Technologies	R1	Incrementally Innovative	S-O/T	Brazil	Agriculture	Retail

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
144	De Souza et al. (2021)	waste: Understanding innovative marketing strategies in the context of an emerging economy	Optimization of the prodution process	Technologies	R1	Incrementally Innovative	S-O/T	Brazil	Agriculture	Retail
145	De Souza et al. (2021)		Optimization of the prodution process	Technologies	R1	Incrementally Innovative	S-O/T	Brazil	Agriculture	Retail
146	De Souza et al. (2021)		Optimization of the prodution process	Technologies	R1	Incrementally Innovative	S-O/T	Brazil	Agriculture	Retail
147	De Souza et al. (2021)		Optimization of the prodution process	Technologies	R1	Incrementally Innovative	S-O/T	Brazil	Agriculture	Retail
148	Kafel et al. (2021)	Microplastics risk at the interface of circular economy, quality and food safety in Poland: a casa study	Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Poland	Various	Processing
149	Kafel et al. (2021)		Optimization of the prodution process	Materials in inputs	R1	Incrementally Innovative	T	Poland	Various	Processing
150	Kafel et al. (2021)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Poland	Various	Processing
151	de Vasconcelos et al. (2021)	Circular Economy and Sustainability in the Fresh Fruit Supply Chain: A Study across Brazil and the UK	Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Brazil/UK	Agriculture	Whole SC
152	de Vasconcelos et al. (2021)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Brazil/UK	Agriculture	Whole SC
153	de Vasconcelos et al. (2021)		Reprocessing	Animal feed	R2	Conventional	NA	Brazil/UK	Agriculture	Whole SC
154	de Vasconcelos et al. (2021)		Reprocessing	Nutrients	R2	Conventional	NA	Brazil/UK	Agriculture	Whole SC
155	de Vasconcelos et al. (2021)		Reprocessing	Materials	R3	Conventional	NA	Brazil/UK	Agriculture	Whole SC
156	de Vasconcelos et al. (2021)		Sharing of resources	Tangibles	R1	Incrementally Innovative	S-O	Brazil/UK	Agriculture	Whole SC

ID	Reference	Title	Processs	Goal	4R	Innovativeness	Type of innovation	Country	SC type	SC stage
157	de Vasconcelos et al. (2021)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Brazil/UK	Agriculture	Whole SC
158	Lima et al. (2021)	Water and wastewater O in a food processing industry using water pinch technology	Reprocessing	Water	R4	Incrementally Innovative	T	Brazil	Water	Processing
159	Novara et al., (2022)	Climate Smart Regenerative Agriculture to Produce Sustainable Beauty Products: The Case Study of Snail Secretion Filtrate (LX360®)	Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Italy	Agriculture	Production
160	Novara et al., (2022)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Italy	Agriculture	Production
161	Novara et al., (2022)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Italy	Water	Production
162	Novara et al., (2022)		Optimization of the prodution process	Materials in inputs	R1	Conventional	NA	Italy	Agriculture	Production

Table S3 Circular practices identified classified per level of innovativeness and circularity

	Practices Overview			
4 R	**Conventional**	**Incrementally Innovative**	**Radically Innovative**	**References**
Reduce	Substitution of chemical fertilizer with organic one (obtained e.g., by manure or straw)	Sharing of resources (e.g., food, fertilizer, equipments)		Principato et al. (2019); Kowalski and Makara (2021); Fernandez-Mena et al. (2020); de Vasconcelos et al. (2021); Rodrigues et al. (2021); Maass and Grundmann (2016)
Reuse	Organic residues used as animal feed or compost; by-products valorization to generate human food			Cortes et al. (2021); Sellitto et al. (2019); Principato et al. (2019); de Vasconcelos et al. (2021)
Recycle	Use of food residues to produce pet food (e.g., fishmeal, wet foods)	Extraction of compounds from surplus food (e.g., flavonoids from citrus and vitamin D from mushrooms); By-products valorization (e.g., grape pomace into grapeseed oil, wine lees into calcium tartrate, rice straw into building material-bran oil into food emulsifier-bran proteins)	Extraction and valorization of food waste and by-products (citrus to obtain cellulose and paper, cheese whey permeate to obtain substrate for the production of bacterial cellulose used in antimicrobial materials)	Cortes et al. (2021); Sellitto et al. (2019); Kowalski and Makara (2021); Kerdlap et al. (2020); Laso et al. (2018); Santagata et al. (2017); Cardoso et al. (2020); Ncube et al., (2021); Overturf et al. (2020); Zuin et al. (2021); Rollini et al (2020); Boccia et al. (2021)
Recover	Anaerobic digestion with production of biogas and digestate; Use of waste for composting (e.g., pasta, straw, pruning waste, food waste and leaf-litter); Incineration of food loss with biogas recovery (anchovy)	Use of bio energy sources (e.g., biofuel from grapeseed oil, bio-based steam from stalks and pruning, biofuel and bio steam from meat and bone meal, bioethanol from cassava peels, bio-oil and biochar from pomace and tree pruning)		Keng et al. (2020); Sellitto et al. (2019); Laso et al. (2018); Brenes-Peralta et al. (2020); Zabaniotou et al. (2015); Zhu et al. (2019); De Sousa et al. (2021); Kerdlap et al. (2020); Boccia et al. (2021); Kılkış and Kılkış (2017); Fernandez-Mena et al. (2020); Principato et al. (2019); Liu et al. (2018)
Disposal	Incineration and landfilling without energy recovery			Marrucci et al. (2020); Principato et al. (2019)

Chapter 3 Circular economy in the agri-food sector: Insights into Portuguese companies' practices.

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Circular economy in the agri-food sector: Insights into Portuguese companies' practices.

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Abstract

Relevant cultural and financial factors hamper circularity in Portuguese agri-food sector companies. To capture so, an empirical analysis of circular practices in agri-food companies was carried out. Being the agri-food sector central to the Portuguese economy and the numerous circular economy initiatives in the Country, the study aims to comprehend how circularity is achieved from an environmental, social, and financial perspective in Portuguese companies of the sector. Therefore, a survey of a selected sample of companies identified 9 examples of organisations involved in circularity to interview.

Results evidence: (i) strong cultural and financial barriers in implementation and evaluation; (ii) generation of social value through community-centred initiatives and collaborations with local companies; (iii) urgency to valorise and communicate financial impact to conquer new funding opportunities.

The analysis contributed with new knowledge on the social value-creating capacity of circularity and the impact on companies' financial performance in the agri-food sector, providing interesting future insights into academia and policymaking.

Keywords: Circular Economy; Agri-food sector; Circularity assessment; Interviews; Financial performance; Social value creation.

1 Introduction

The agri-food sector (AFS) is traditionally linked to the linear 'take-make-dispose' paradigm, the sustainability of which is now debated [13]. The Food and Agriculture Organization (FAO) estimated that today one-third of food produced worldwide is lost or wasted through the supply chains, while 795 million people face hunger [25]. This will worsen by the expected population increase in 2050 which will additionally increase the food burdens [68]. In this context, the circular economy (CE) reconsiders waste as a resource, promoting closed loops of product lifecycles [13]. It is emerging as a sustainable paradigm contributing to the ecological transition by generating economic advantages, reducing environmental degradation, and promoting the well-being of the present and future society [1]. In addition, as highlighted by [66] in a systematic literature review on the meso and micro level of circularity practices in the AFS, circularity appears already embedded in the agri-food dynamics. The prevalence of conventional circular practices among scientific literature case studies suggested the maturity of the sector in implementing CE. However, it is relevant to understand if what emerged from this literature review is in line with the sector's reality. Indeed, considering agri-food companies' perspective is essential to have a complete vision of the food system, limiting the gap between academic theoretical models and practitioners' reality [68] and better understanding why companies still struggle to translate circularity principles into business strategies [62].

CE has a strategic value in the AFS because it reduces environmental impacts, promotes community health and employment, and reduces companies' operating costs [46]. Thus, more empirical studies are required to explore the implementation and characterization of CE in the sector.

Europe has been ahead in terms of CE implementation in the industrial sectors with several regulations as drivers, such as the Green Deal [19]. In this context, Portugal is a valuable case study to explore CE dynamics and empirical evidence. Indeed, in this sense, the AFS is a pillar of the Portuguese economy. Food production is one of the main engines of its manufacturing industry, characterizing 14.5% of total sales in 2016 [26]. Moreover, it is one of the largest employers in the country, with approximately 294,000 people and 135,000 companies [27]. In the last years, Portugal has promoted different CE-oriented initiatives in the agri-food context. Examples are the Alentejo Circular project [2] to foster circular practices in pork, wine, and olive production, representing the excellence of the Alentejo region, or the "REiNOVA Si" project [60], a cross-border collaboration between Portugal and Spain to map circular best practices for the AFS in SMEs. For these reasons, Portugal has been chosen as the country location of the proposed empirical analysis. Thus, this study aims to obtain an improved understanding of how Portuguese companies of the AFS consider CE within their activities. For this purpose, the authors conducted nine semi-structured interviews engaged in CE, previously specifically selected through a survey administered to a convenient sample of Portuguese AFS companies.

Previous research explored several features of CE in AFS [32, 76, 1]. However, companies still face several challenges to CE adoption in the sector [43] among them, the lack of shared assessment systems for measuring CE [57]. This makes it difficult for companies to evaluate the impact of circularity on their performances and consequently to further include circularity in their business strategy [43]. Moreover, circularity is still associated with the environmental scope [66], while limited attention has been posed of the social and financial value it generates in the AFS.

2 Theoretical overview

2.1 CE IN AFS

The aim of this sectionis to provide ~~the reader with~~ an overview of how CE is addressed in the AFS context, given the interest that the topic has received since the introduction of the CE action plan [18]. For further insights, please refer to other review works [17, 66]. Among the contributions, relevant is the work of [6], which mapped CE agricultural practices for energy production. The analysis pointed out that the AFS has been closing the loop for materials and waste for a long time, thus evidencing how circularity is not new in the sector. [17] collected examples of circular practices and assessment tools along the agri-food chain, emphasising the lack of shared assessment methodologies to compare circular practices among different supply chains. More recently, [68] explored inter- and intra-organizational practices of CE in the agri-food context, evidencing the limited consideration of the social perspective. On the contrary, [56] analysing CE's impact on value optimization in the food supply chain, highlighted the social value generation of CE e.g., by promoting good practices for sustainability along the supply chain and the surrounding community. Moreover, recent European policy interventions included circularity in their scope. Specifically, the EU Taxonomy Regulation [20], which aims to support environmentally sustainable investments, and the Corporate Sustainability Reporting Directive (CSRD) [21], which aims to move Europe towards a carbon-neutral economy by 2050. This new directive requires not only more detail in reporting but also involves more types of companies, e.g., listed Small and Medium Enterprises- SMEs [20]. Despite the increasing necessity for companies to link circularity to financial outcomes, there is a lack of studies that explore how CE implementation impacts the financial performance at the company level, especially in the AFS, which already indicated financial resources as a key driver and barrier [47, 23]. Companies will apply the new rules in 2024's financial year [20]; this makes it urgent to consider new methodologies for measuring and reporting the financial impacts of the CE.

Despite CE implementation in the AFS being widespread in the literature, there are still relevant gaps which limit the adoption of circularity, especially in SMEs. Given the identified lack of literature on CE assessment, CE social value creation and financial impact, these topics will be further explored in the following sections.

2.2 Barriers and benefits to CE assessment

The CE assessment is a crucial driver since it allows tracking and quantifying progress towards circularity [66]. Several assessment approaches are available in the [50, 12], but their application is still limited in the private sector [62, 70]. Only a few studies explore empirically the benefits and barriers of circularity assessment. [62], who investigated the assessment practices of CE frontrunner companies in the private sector in Italy and Holland, highlighted that many of the perceived internal barriers are in common with the measurement of sustainability. These include the presence of methodological issues, as the lack of assessment standards, often translated into a lack of interest or awareness for the assessment by clients. Among the key benefits, the improvement of transparency stands out, which increases collaborative opportunities for companies. [15], analysing the public sector, identified relevant cultural and structural challenges for CE assessment. The first regards the lack of awareness of the necessity to measure CE, while the latter considers the absence of obligation for the assessment, which leads to a lack of clarity of targets and goals. Although there are already studies that have synthesised and analysed the evaluation tools available for AFS [24, 42, 55, 61], the assessment of circularity is still limited [11]. One possible explanation is the high number of circularity indicators evidenced for the AFS [72], which may generate confusion among practitioners on which to choose and what boundaries to give to their assessment practice. However, the reasons for this reduced measurement of circularity are scarcely investigated in this sector. Thus, understanding companies' perspectives is essential to examine the adoption of such tools and to identify the main obstacles and benefits encountered. The lack of empirical evidence on CE assessment in the AFS and the benefits and barriers faced led to the following research sub-questions (RSQs):

RSQ1A: How do Portuguese companies of the AFS assess CE?

RSQ1B: What are the main barriers perceived for assessing/not assessing circularity in the sector?

RSQ1C: What are the benefits perceived in assessing circularity in the sector?

2.3 Social performance

CE adopts the triple bottom-line vision of sustainability, which includes the environmental, social, and economic perspective [60]. It proposes to enhance the well-being of the present and future generations, but it seems to address the social aspect only implicitly [29]. In literature, [40] mentioned CE's capacity to increase employment and foster participative democratic decisions. Such importance is confirmed by the inclusion of the sustainable development goals (SDGs) which includes the social dimension in the CE agenda [53]. Nevertheless, there is no consensus on how CE can enhance social value [59]. One relevant issue regards the lack of a clear definition of what is meant by social value for companies since it includes several stakeholders and is context-related [73]. [53], in their systematic review, identified "employment" as the most relevant feature regarding social value in the company setting, followed by "health and safety", and "democratic participation". Job creation is the most common social metric in literature. Nevertheless, it is not the only social category affected by CE practices [74]. Social value can be understood as a value-added service or as an outcome of CE implementation, where the latter received limited attention in the literature. For this reason, [5] conducted a review, exploring the social value derived from CE practices in agri-food eco-industrial parks; the analysis showed that social value, understood as the achievement of social equity from industrial operations, is generally understudied and often limited to tackling food security and resilience. Addressing this gap, this study aims to broaden the discourse on the social value generated from circular practices through the empirical analysis of what happens in the sample of CE-experienced companies analysed. This has generated the following RQs:

RSQ2A: How does CE generate social value in the AFS?

RSQ2B: How do companies of the AFS include social value in their circular strategies?

2.4 Financial performance

Growing environmental, economic, and social issues have led international organizations and country systems to devise strategies for sustainable development; among them relevant is the Environmental Social and Governance (ESG) framework [45]. The European Banking Authority (EBA) defines ESG principles as "environmental, social or governance matters that may have a positive or negative impact on the financial performance or solvency of an entity, sovereign or individual" [16, p. 31]. Financial regulation actions like the European "Action Plan: Financing Sustainable Growth" already defined a roadmap for the financial system to approach sustainable investments. This flow encouraged the identification and quantification of ESG risks through different standards and taxonomies, like the EU taxonomy [16]. In this sense, the EU taxonomy proposed a classification system for low-carbon and resource-efficient economic activities and recognizes CE transition as one of its environmental objectives [16]. Indeed, ESG assessment allows companies to discover improvement areas and potentially identify the best strategies to start their journey into circularity [75]. The "Taxonomy Regulation" [21], and the Corporate Sustainability Reporting Directive (CSRD) [20] have pushed financial institutions to introduce CE terminology [52].

Moreover, previous studies evidenced a positive relationship between ESG adoption and companies' financial performance (FP) [45]. Specifically, FP is a meta-construct that measures the profitability of business strategies in terms of effectiveness and efficiency, which is a relevant factor for companies' transition to CE [37, 31]. However, the lack of guidelines and empirical studies makes it difficult for companies to capture and communicate the effects of circularity on their FP [37]. Today, the FP of circular companies is mainly measured through short-sight accounting- indicators, which do not capture circular timelines [38]. Indeed, compared to linear ones, CE investments show longer timelines and involve multiple life cycles [38]. Indeed, positive cashflows are not generated at the beginning of the product's life [3], and this increases the uncertainty for future cashflows [30].

Some studies, in mapping circularity, ingenerated the AFS, identify economic indicators that can quantify production costs and the economic value generated, however, they are not strictly financial indicators [55, 42]. Moreover, as in the measurement of circularity in general, there is no information on their effectiveness in measuring circular performance. Overall, CE financial assessment should involve the identification and re-evaluation of relevant costs and revenues connected to company processes, capturing the characteristics appointed by circularity [66]. However, the heterogeneous risk profile that characterizes companies involved in circularity makes it difficult to define a standardized financial instrument to measure and monitor financial performance [30]. As a result, the following RSQs are proposed:

RSQ3A: How does CE impact the FP of companies of the AFS?

3 Methods

The present study adopts a mixed research approach based on a survey and following interviews. The use of a mixed method allows us to better tailor the research method to the aim of the analysis and the characteristics of the sample. Conducting interviews after a survey allows to dive deeper into a topic, e.g., asking for clarifications in case of unclear survey responses [54]. The approach is articulated into a three-step methodology represented in Fig. 1.

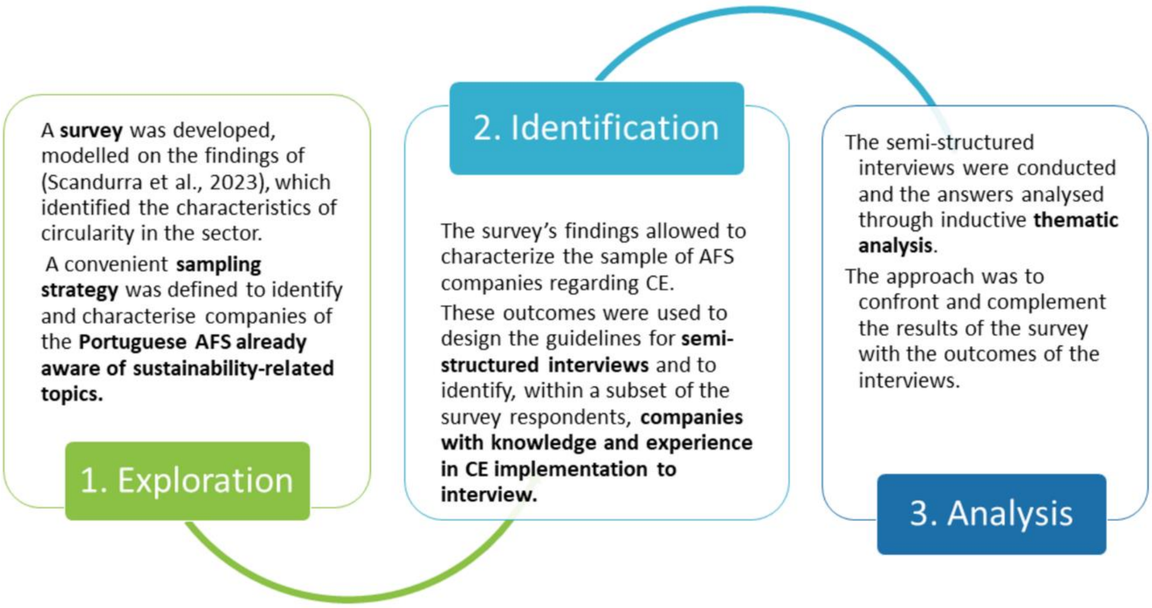

Fig. 1 Overview of the three methodological steps of the study.

3.1 Step 1-Exploration

To achieve the goal of interviewing companies with experience in the field of CE, agri-food networks that represent companies that are in touch with circularity and sustainability issues were first identified; thus, a purposive sampling method was adopted. Purposive sampling is a non-probability technique that allows the selection of respondents that address the study aim and, by doing so, increases the depth of the analysis [8]. The sample includes only companies whose attributes meet the research goal of the study [63]. In this case, the authors included only private companies directly operating in the AFS: i) companies' members of the non-profit association "PortugalFoods" [57], which brings together food industry companies and entities from the Portuguese scientific ecosystem; ii) companies' part of the project "Alentejo Circular" project [2], developed by the Instituto Soldatura e Qualidade (ISQ) and the University of Évora, to mobilize economic actors towards circularity in the olive oil, wine, and pig farming in the Alentejo region (Portugal).To evaluate the implementation of circularity within the sample, a survey was developed. The survey was articulated into three sections as presented in Fig. 2.

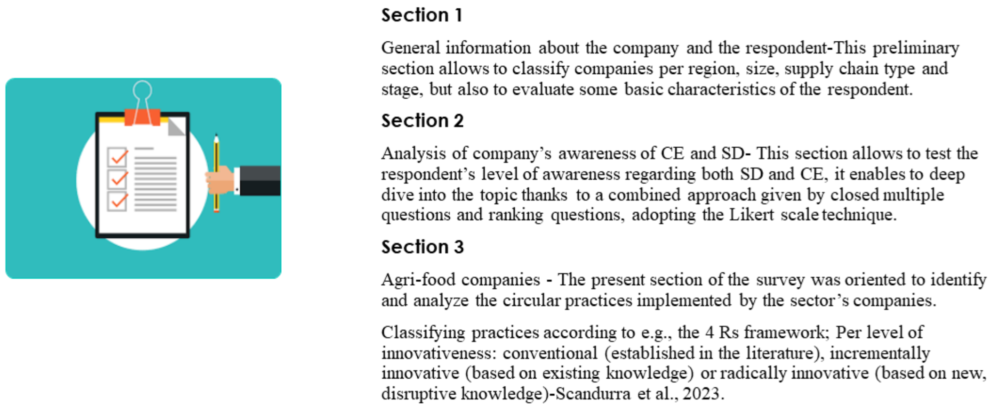

Fig. 2 Overview of the survey structure

More detail on the survey structure is provided in Table 1 of Supplementary Materials. The survey enables the authors to collect information regarding companies' backgrounds, which later helps the interviewers to drive their questions to the core subject [9]. The survey was originally written in English and subsequently translated into Portuguese. It was tested in both languages by the researchers. The survey was designed through Microsoft Forms. It was delivered with email invitations on 26 January 2023 and was open until 13 March 2023. The last question of the survey asked for respondents' interest in continuing the research by having follow-up interviews with the researchers.

3.2 Step 2-Identification

At the end of the survey, responses were translated into English by the authors and exported to Microsoft Excel. Information was analysed through an exploratory and descriptive approach based on respondents' knowledge and application of CE. For this, descriptive statistics were applied to characterize the companies and their reported CE practices. These findings allowed to the identification of CE attributes in the sector and were used to get insights to design a semi-structured interview guide of open-ended questions with the following dimensions: i) the CE drivers and barriers, ii) the CE assessment, iii) the CE capacity to generate social value, and iv) the impact of CE on companies' FP. In the survey, 28 companies claimed to include initial or consolidated stage-circularity principles in their activities; however, only 16 companies described practices that can be classified as circular. Among the 16 implementing companies, 9 with CE experience coherent with the RSQs were available for the following research step. Thus, the final interview sample consisted of 9 companies.

3.3 Step 3- Analysis

After the survey, 9 semi-structured interviews were conducted to understand in detail how the companies of the sector implement and monitor circularity. The interviews were conducted in English either via video call (n=8) or in written form (n=1), depending on the interviewers' preference, and at time of their choice, between March and June 2023. Moreover, all the interviews were conducted in the presence of a native Portuguese speaker to facilitate the interviewee and reduce possible bias due to language.

The call interviews lasting, on average 60±34.5 min, were video recorded for accuracy of transcription and analysis, following participants' permission, and the recordings were anonymously transcribed verbatim.

Subsequently, the 9 interviews were analysed through an inductive thematic analysis [7]. The choice of inductive coding, namely identifying themes from the data itself, is due to the exploratory nature of the present analysis since inductive coding has proved to be useful in exploring novel research areas [35]. The analysis was performed on a qualitative data analysis software, QSR NVivo 1.4 [58]. During the process of coding and identification of themes, inconsistencies and discrepancies were monitored to ensure a deep understanding of the text. To illustrate the analysis, consumer direct quotes were transcribed, serving as a description of the theme explored. Note that the same extract may be assigned to more than one theme.

4 Results

4.1 Survey Sample characterization.

The survey was administered to 148 companies and completed by 31 (response rate: ≈ 21%). The main characteristics of the survey sample are summarized in Table. 1.

Table 1 Descriptive overview of the survey sample. Note that the percentages of responses may be higher than 100% since respondents could choose more than one option.

Main characteristics	Survey respondents (n=31)
Company size	
Micro companies (0-10 employees)	10%
SME (0-250 employees)	61%
Large companies (>250 employees)	29%
Company location	
North	32%
Centre	19%
Metropolitan Area of Lisbon	23%
Alentejo	26%
Supply chain stages	
Processing and packaging	77%
Primary production	29%
Food distribution	26%
Handling and storage	29%
Retail	14%
Hotels and restaurants	3%
Respondent's department	

Sustainability-related	23%
Production	13%
Management	23%
Marketing and Sales	19%
Research and Development	6%

4.2 Survey responses.

In answering about their vision of CE, 42% of respondents depicted it as a societal paradigm which aims at producing and consuming economical goods and services respecting the environment, embracing a systemic vision of it, or 29% as a paradigm focused on a regenerative use of resources, closing energy and material cycles, fostering an environmental one. Lastly, present but limited are the economic and social conceptions of the term. Respondents largely consider CE one of the tools for achieving SDGs, but not the only available. Moreover, they tend to focus on the environmental benefits connected to CE. The social dimension appears as a questioned and unclear factor since most of the respondents are not able to agree or disagree with CE's capacity to increase this kind of value in companies.

Moving to CE implementation, respondents indicated the practices adopted in an open-ended question; 28 circular practices were identified out of the 31 companies. Note that the number of practices does not match the number of companies in the sample, since respondents could describe more than one practice. As shown by Fig. 3, most of the 31 respondents identified incrementally innovative practices implemented (e.g., fixation of nitrogen by rhizobia leguminous plants). Conventional practices (e.g., use of organic waste to produce compost) characterize a limited fraction of the sample. None of the respondents claimed to have implemented radically innovative circular practices.

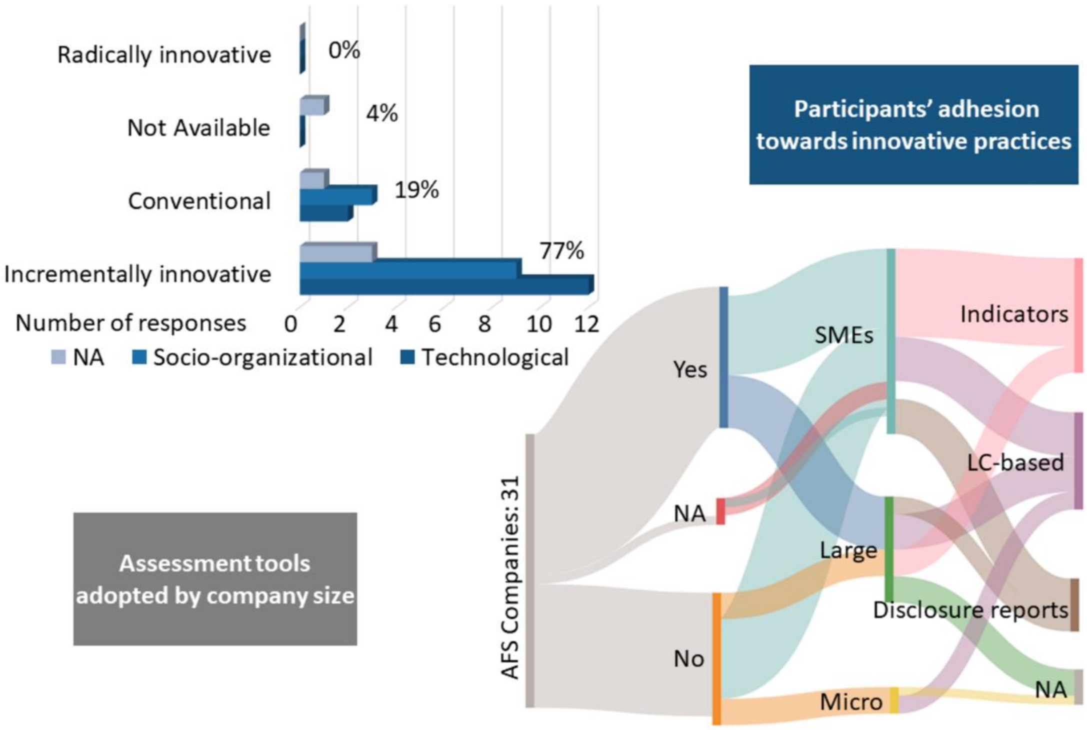

Fig. 3 Overview of the principal survey findings

In implementing CE, respondents claim more than one R strategy, as a large portion adopts all the 4 Rs (23% of the sample, 4 from large companies and 3 from SMEs). Whereas only SMEs focused on single Rs; reuse and recycle strategies are the most adopted and reduced ones the least considered. Concerning the practices identified, the 28 respondents that indicated a specific goal, represented in Fig. 4, were mainly directed to the recycling, or reusing of materials (4 large and 4 SMEs). This could be explained by the fact that 77% of the sample belongs to the "processing and packaging" supply chain stage. Another relevant portion (3 large and 4 SMEs) was directed to the production of food and feed. The generation of soil nutrients (4 large and 4 SMEs). Some practices (3 large) are directed to sensibilization on sustainability-related topics. The production of energy is limited in the sample (2 large and 1 SME). Finally, some of the companies put regenerative farming techniques in connection to CE (1 large and 1 SME).

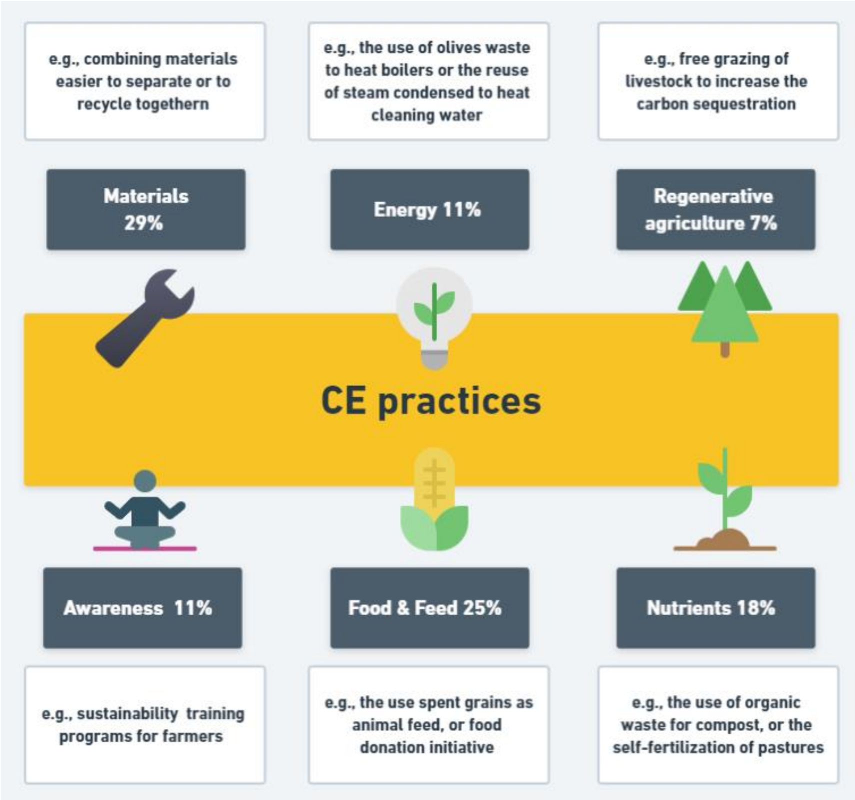

Fig. 4 Overview of the 28 circular practices described in the survey

Concerning the measurement of circularity, approximately 60% of the companies that assessing CE are SMEs and the other 40% are large companies. Of the 15 assessing companies, around 64% of the assessing companies did not explain the type of indicators used, the remaining ones adopted lifecycle-based tools and disclosure or communicative reports, some in line with Global Reporting Initiatives (GRI) standards, others not specifying the internal or external nature of such communications. Despite a significant part of the sample states not measuring circularity, many companies use some of the proposed monitoring tools. In detail, 10 of the 15 non-assessing companies adopt lifecycle-based tools (50%), specific indicators (40%), or disclosure reports (10%).

4.3 The interviews

The analysis of the nine interview responses provided an in-depth understanding of how circularity is implemented and monitored in a convenient sample of Portuguese agri-food companies (Fig. 5). Three broad levels of analysis were identified which combined many themes, cutting across the different topics of discussion. The sample is diversified in terms of size, especially considering the percentage of large and SME realities. Most of the companies are involved in processing and packaging supply chain stages, whether the retail stage has limited impact. In terms of supply chain types, the drinks and beverage segment are the most common, while livestock and the category various (namely, one retail company) are the least represented.

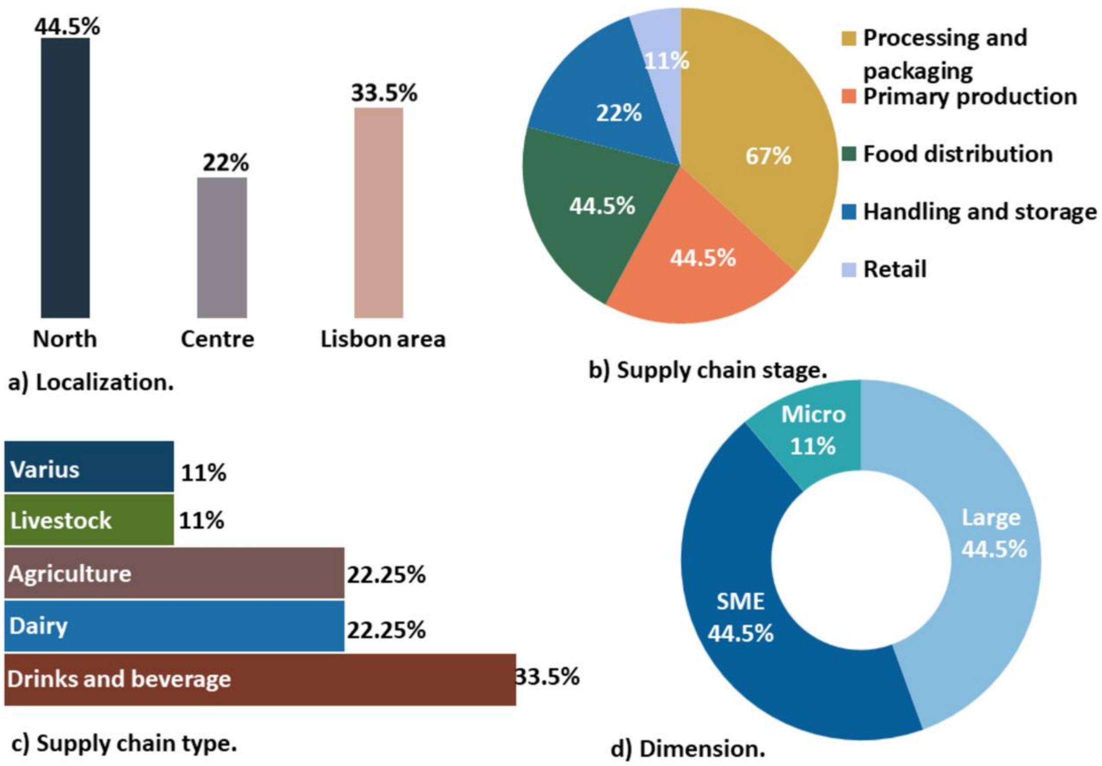

Fig. 5 Descriptive overview of the interview sample. Note that the percentages of responses may be higher than 100% since respondents could choose more than one option

4.3.1 Drivers and conceptualization

The adoption of CE is determined by several factors. Regarding the environmental implications of CE, participants emphasize the importance of a clear strategy for the environment, for the company's long-term viability. The environmental considerations are often coupled with the economic ones. As observed, adopting environmentally friendly practices saves resources that would otherwise be needed to offset the impacts of polluting practices. In detail, the economic implications are largely related to cost reductions due to processes and material efficiency. Overlooked are the social implications of circularity, namely, engaging the surrounding community e.g., through job opportunities or donations, but also, as a potential guide for people's choices, exploiting the scope of the company's activity. The generation of brand value is as well reported by the interviewees, in the sense that CE improves brands, making sustainability and circularity distinctive traits of a company's products, and allowing their recognition on the market.

Besides the drivers, companies mentioned company culture, which meant the willingness to embrace CE by the company's management. Circularity requires a strong commitment. In small companies, this is even more important. CE investments are perceived as something not related to the companies' core business that requires sacrifices for the company.

Interestingly, CE is not perceived as a new concept but a renewed one. Some of the participants interviewed consider it as part of conventional agri-food practices, even if companies use a different name for it. So, the sector does not need to be reshaped to circularity (Interviewee #8, Large). One tangible example is given by the reuse of whey. For a long time, whey was just poured into the rivers or the soil but during the 1940s some companies started to reuse it as animal feed. Over the years, companies kept adding value to the whey, e.g., today it is sold to obtain protein extracts for food, feed, or cosmetic products.

In the interviews participants also reported different barriers that they faced when implementing CE, which can be categorised into financial, cultural, and legislative. Implementing CE requires considerable investments and additional costs. That is, the additional cost of recycled materials is not shared along the supply chain, so food companies can feel squished in their chain, as one company (SME) mentioned. The cultural barriers concern internal and external factors. The first regards companies' scepticism around CE-related investments, while the latter concerns retailers' and consumer's lack of interest or awareness. For the interviewees, consumers are perceived as reluctant to change their mindset, given the importance of convenience factor in consumers life (Interviewee #6, Large). Finally, legislative issues relate to the uncertainty of upcoming regulation which may impose new measures on companies.

4.3.2 CE assessment: benefits and barriers

The five participants who stated not conducting any form of CE assessment in their corresponding companies, one large and three SMEs discussed the reasons for their choice and the barriers perceived. The root cause seems cultural since CE assessment is not perceived as a priority. Consequently, companies state of not aware of the methodologies available for CE measurement. Only one large company is approaching the assessment, focusing on the circularity of packaging.

Different barriers and benefits of CE assessment were debated by our interviewees (Table 2). Based on the literature, four barriers emerged. The company's company seems influenced by the small size of companies, which implies a limited budget and operational team. The structure issues evidence the non-compulsory nature of the CE assessment, which makes companies not interested. The Technical challenges stress the complexity and slowness of the assessment process. The Lack of external demand highlights the difficulty of involving stakeholders in the assessment. However, demand for assessment by actors like consumers would push companies to start assessing, as declared by one SME. The not-measuring companies claim they will give it more attention shortly due to external pushes from the supply chain and legislation.

In contrast, the four participants belonging to companies, three large and one SME, which started assessing CE discussed the perceived benefits obtained. Answers were grouped into i) internal insights, which deals with internal improvements margins, and ii) external communication benefits, which allows companies to improve their reputation (e.g., by offering consumers quality products with low environmental impacts), but also to engage both consumers and employees. Finally, one company mentioned the need to anticipate the legislation and be ready for the future, so introducing CE measurement tools now will put the company on the right path for the future.

Moreover, these companies mentioned the importance of benchmarks to compare with other companies, generating a virtuous path of development. For small-size companies, having benchmarks with larger companies is essential, they are on average more likely to try out different paths as they have more resources at their disposal compared to SMEs (Interview #9, Small).

Table 2 CE assessment: Benefits and Barriers

Barriers	**Description**	**Reference**
a) Company's capacity	Lack of a company structure able to support the assessment and control of CE.	Roos Lindgreen et al., (2022); Droege et al., (2021).
b) Structural issues	Skepticism towards measuring being perceived as non-rewarding, and the lack of legislative obligation for CE assessment.	
c) Technical challenges	Perceived complexity in the assessing process. CE because the process is considered long and complex.	
d) Lack of external demand	Supply chain partners lack interest.	
Benefits	**Description**	**Reference**
i) Internal insights	Process efficiency, impact reduction and decision-making support.	Roos Lindgreen et al., (2022)
ii) External communication	Improve the company's reputation. Sensibilize consumers and employees to the importance of impact reduction.	

The tools mentioned by the interviewees are reported in Fig. 6. Some benefits and challenges were evidenced in using such tools, e.g., GRI reporting standards require an external audit but will prepare the company for the future, given the increasing attention to sustainability reporting (Large). LCA, which identifies and quantifies all the resources consumed and the emissions on the environment related to goods or services [36], allows to valorise the improvements made by the company but is not suitable for comparison with competitors and its high technicality makes it difficult to communicate its results to other departments (Large). Whereas concerning tailor-made indicators, one company (SME) indicated the use of a platform for regenerative agriculture where companies from different sectors share the indicators adopted as a guide to start the assessment journey.

Eventually, participants were asked about first the relationship between CE and sustainability and then, only the assessing companies, about the possibility of using the same monitoring tools for sustainability and CE. Most of the interviewees consider CE as part of sustainability, one company (Large) argued a different scale of intervention between the two: CE is focused on the business perspective, including some stakeholders, while sustainability looks also at the overall supply chain. Another considerable portion considers the concepts as interconnected, without clarifying their specific features. Only one company (SME) warned by adopting the two concepts interchangeably, mentioning potential rebound effects. Concerning the assessment, most of the companies adopting CE tools agree on using the same tools for both, while a marginal portion feels they do not have enough information to answer.

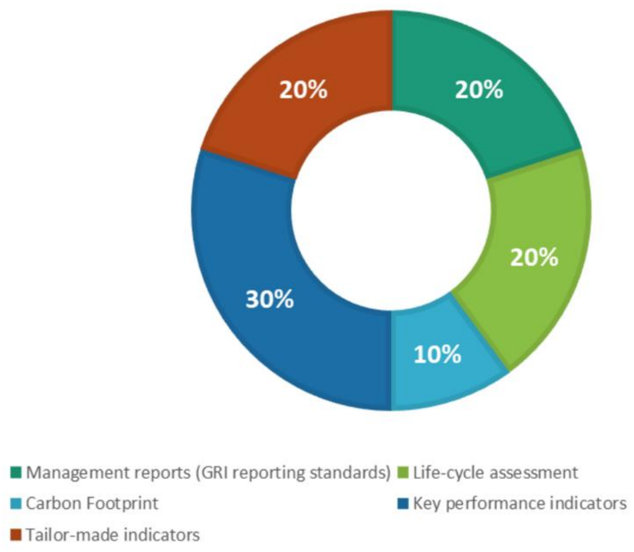

Fig. 6 CE Assessment tools adopted

4.3.3 Social value

The social impact of CE was referred to by our participants at two levels: i) possible social impacts, and ii) effective social impacts. The first considers the potential capacity of CE to generate social value; this statement is generally agreed upon by the sample. Going into detail, respondents mentioned the generation of social inclusion, cohesion, commitment, and employment. As participants outline, CE improves process efficiency and generates new business opportunities, leading to additional revenues and potentially more employment. Some participants mention CE's capacity to introduce sustainability into the individual mindset, enhancing responsible consumption. Finally, social cohesion (people in a neighbourhood or region feeling more strongly connected) and inclusion (connecting employees with a distance to the labour market, more diversity) are limitedly mentioned in the sample.

The second is inspired by the framework of [44] (shown in Fig. 7). a) Employees are focused on ensuring employment conditions, as well as involving employees in decision-making processes. b) Local community is oriented to creating assets and infrastructures for the community, but also on the effect of CE on social relationships. Interviewees evidenced the importance of opening up to neighbours' companies to develop collaborations able to develop a shared upgraded solution for CE, supporting the community. c) Stakeholders' participation focused on companies influencing supply chain partners, namely distributors and suppliers by establishing strict provision requirements, or being influenced by retailers and consumers. However, within stakeholders' participation, the role of consumers is ambivalent. Some companies consider consumers interested in the sustainability of their choices, although not always willing to accept the price differential for product quality, but the majority, perceive them as unresponsive and resistant to changing their purchasing habits. According to the interviewees, companies perceived academia and other companies as valuable partners. Circularity encourages companies to be receptive to surrounding businesses, even if they are still in start-up form. Then, d) Policy, meant as policy impacts are limited in the sample and expressed by pushes for policy changes.

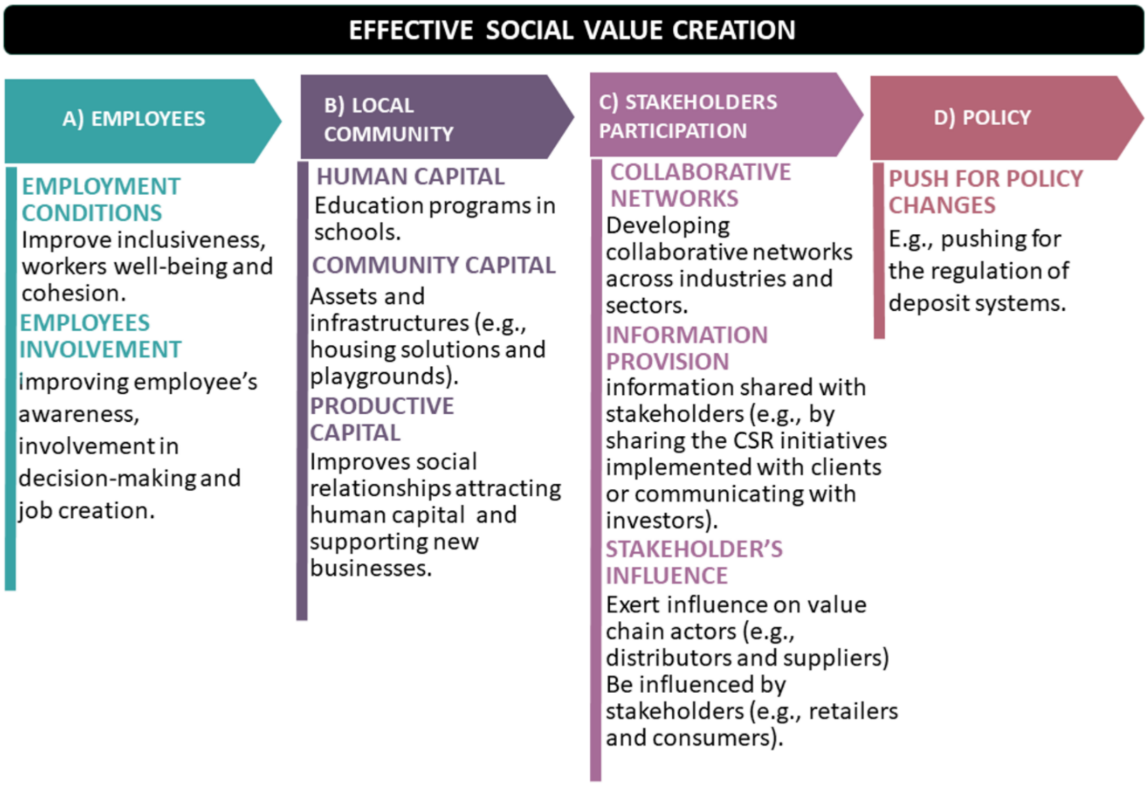

Fig. 7 Effective social value creation scheme. Adapted from Labuschagne et al. (2005)

4.3.4 Financial Performance

All the participants interviewed agree that CE has a clear impact on their FP. Cost reduction is the main benefit associated due to increased efficiency in inputs and resources.

Some companies stressed the relationship between the circular practices implemented and positive FP. Specifically, linear practices generate costs for external input purchase but also to costs to restore the ecosystem equilibrium. CE also allows entering new markets and reaching more consumers and a positive brand image. CE-related investments offer valuable payoffs, especially related to product quality, and communicated through marketing initiatives. However, according to our interviewees, they need time to be profitable and involve additional costs difficult to forecast.

The analysis identified the use of ordinary monitoring tools (e.g., ROI, ROA, payback periods) to measure the FP of circular-related investments. One company, however, is working on a framework to value products by combining financial and sustainability criteria. Such tool will allow to overcome the dichotomy between costs and revenues to include key sustainability areas. As reported by one interviewee (Interviewee #8, Large), the brand manager was solely focused on the financial performance, but now is starting to familiarize with sustainability and to combine the two perspectives.

Exploring the FP issues to CE (evidenced in Fig. 8), the most relevant is the time constraint. Market's logic pushes companies to focus on short-term financial horizons. The same can be concluded for SMEs, which deal with limited structures and sometimes managers do not have the time to broaden their business perspective since they are too focused on putting out daily fires (Interviewee #5, SME). The Portuguese SMEs of the AFS are additionally challenged in accessing credit, being already overexposed to the banking and financial systems (Interview#5, SME), as evidenced during the interviews. Finally, an increased uncertainty for CE-related investments has been detected, since circularity is an old approach presented as new.

Overall, participants stress the cultural scope of CE. There are various financial indicators, some of which may give negative results in a single year, and this is why they must be assessed from a broader perspective, always considering the overall profitability of the company (Interviewee #2, Large). This is even more important for SMEs, where having a clear picture from the beginning is crucial to balance the investments required and to do so a company leader with such vision is needed (Interviewee #9, SME).

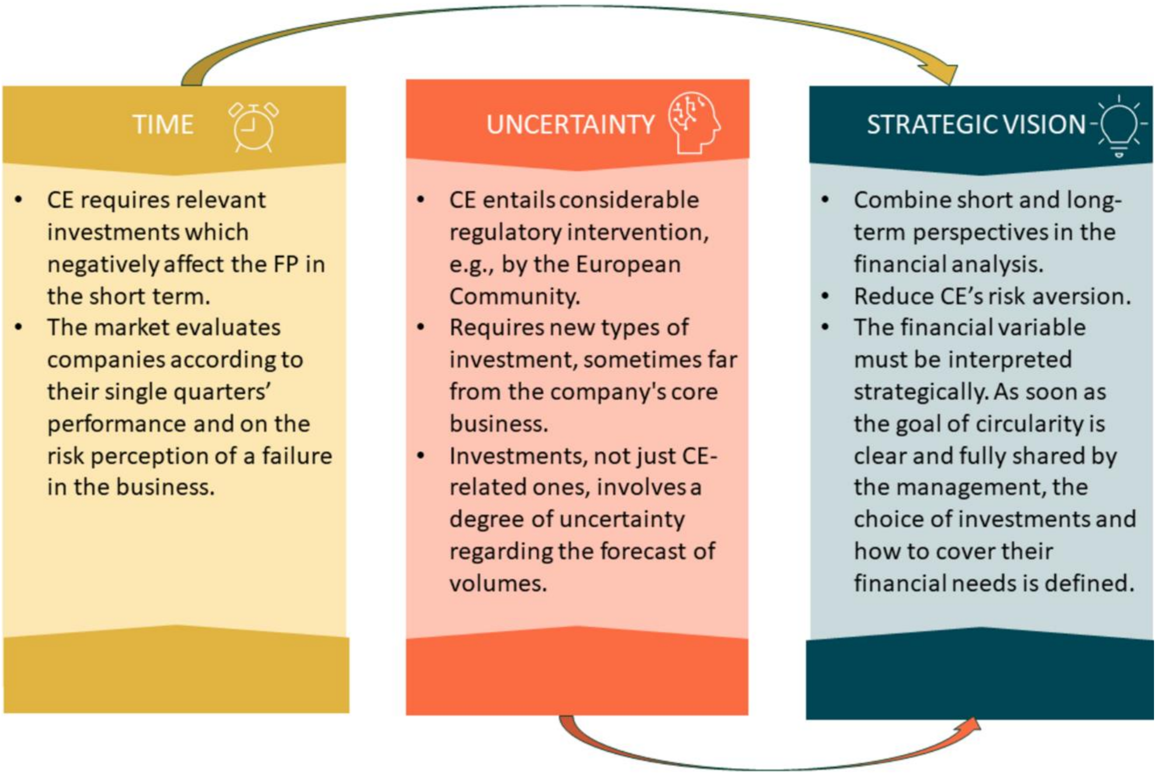

Fig. 8 Main barriers (Time and Uncertainties) perceived in financial assessment of CE strategic visions (investments and proposals for improvement)

5 Discussion section

The survey findings highlighted CE as one of the tools to address several SDG goals. Indeed, the AFS can contribute to SDG12, reducing food loss and waste, to SDG2, eliminating hunger through sustainable agriculture. Nowadays, CE is increasingly considered from a systemic perspective, although the environmental dimension is still strong. The ability of CE to generate social benefits remains the most controversial. Inquiring about the drivers of CE, the interviewees identified environmental protection and financial gains as the main reasons for adoption. The first is focused on reducing the environmental impact and ensuring the long-term viability of the company. The second is the generation of profit margins and cost savings. This confirms environmental and economic drivers as prominent in the sector [47]. Undervalued is still the social driver of CE, as evidenced in literature [51, 29]. Inquiring about barriers, the most impactful are the lack of financial resources and the company's culture. CE is undoubtedly costly for companies; it entails relevant costs for upfront investments [49, 23]. Moreover, the AFS deals with additional risk due to the seasonality and perishability of food products, exposing companies to price risk [47]. The lack of strong commitment and an unfavourable organizational culture proved to hamper the development of the dynamic capabilities necessary to implement CE [23]. The lack of CE consumer awareness [69], the lack of support from supply chain actors, and policy uncertainty are other hampering factors. Especially, consumers are perceived as reluctant to change. Indeed, according to [40], the lack of consumer interest and awareness contributes to slowing down the transition towards a CE.

Regarding the maturity of the sector, results are ambivalent. One-third of the companies interviewed consider CE embodied in traditional agri-food practices since CE principles can be retraced to the roots of the agri-food system. CE has gained momentum as new and disruptive, but it is an old approach. In the past, the optimization and valorisation of waste and resources was a need, more than a choice for companies. Indeed, the same companies connect CE to efficiency drivers. Companies are even unaware of following CE principles. On the contrary, survey respondents largely defined the CE practices implemented as incrementally innovative; in contrast with scientific literature, where the large presence of conventional practices suggested the maturity of the sector [66]. However, some of the practices claimed as innovative are established in the scientific literature suggesting different perceptions among practitioners and academia. The survey was used to identify companies implementing circularity within their businesses, since many of the practices mentioned in the survey lack an explicit link to CE (e.g., the use of solar panels). In this sense, most of the respondents who reported mismatched practices are not operating in sustainability-related departments: this may suggest a lack of internal communication within the company division, since CE practices are known just by the implementing division, evidencing the overall necessity to raise awareness on CE in the AFS. [63], already pointed out the need to invest in education programs at different levels to strengthen the communication of CE in agriculture.

Concerning the assessment, the interview and survey sample present some differences in terms of size of the assessing companies; in the survey, most of the assessing companies are SMEs, while within the interviews, are large companies. However, when asked about the type of assessment, assessing SMEs are vague on the type of indicators included. Interestingly, some of the non-assessing companies claimed to adopt the measurement tools proposed; this suggests the use of such tools not for CE, and companies may not be aware they can use them for CE. Further investigation led to identify the benefits and barriers of CE assessment. Within the interview sample, 4 companies conduct forms of CE assessment, while the remaining 5 do not. First, size matters in CE assessment; only one SME claims to assess circularity, while the non-assessing companies are all SMEs, except for one large company, which is now approaching assessment. Second, companies do not assess because it is not a priority, but it will be soon due to external pressure. The same substantial lack of awareness was registered in the Portuguese public sector and considered the main cause for the lack of assessment [15].

Among the barriers, companies claim the lack of proper structures, meant as resources and human capital to monitor CE, and structural e.g., due to the voluntary nature of assessment [15]. Others are related to external factors like the lack of demand from supply chain partners or clients [10]. Nevertheless, as confirmed in the sample, a push from the consumer would be relevant for CE assessment. Concerning assessing companies, the benefits identified are focused on efficiency due to resource optimization. Secondly, assessment supports decision-making, allowing companies to focus on efficient CE strategies and communicating this information to improve brand reputation. One critical point for large and SMEs is the lack of benchmarks for CE assessment. This severely limits the possibility of contextualizing the assessment outcomes [62]. However, the under-development ISO

59000 series, focused on CE implementation and assessment will better support companies in developing CE and define appropriate benchmarks [34]. Strictly related is the issue of communicability, which emerged by the tool analysis; CE requires technical tools (e.g., life cycle based) which outcomes are difficult to convey both externally among stakeholders and internally among the company's departments. Focusing on the size, the only assessing SME employed tailor-made indicators adapted from an online platform in which other companies shared their experience. SMEs are generally forced to careful choices due to fewer resources but following the example of other companies allows them to understand how and where to focus their efforts. Less mentioned in the sample is the strategic value of measurement to anticipate the expected policy interventions.

Concerning the link between sustainability and CE assessment, both survey and interviewed companies consider CE part of sustainability, recognizing though wider scale of sustainability, which involves the whole supply chain. However, only one company among the interviewed considered that circularity does not always imply improved sustainability due to possible rebound effects, namely the reduced environmental gain at one stage may more than offset the increased emissions at another stage [41]. Overall, the assessing companies agreed on the possibility of using the same tools for both. Such findings suggest confusion over the boundaries of the two concepts, as already assessed in the literature [62].The little interest found on CE assessment suggest that more empirical studies; aimed at increasing the sector's awareness of the potential benefits of measurement and, at the same time, at identifying standardised and sharable forms of measurement based on companies' reality that allow the sector to implement and monitor CE effectively.

From a social point of view, CE pushes companies to move from a firm-centric vision to an ecosystem one, fostering close collaboration with multiple stakeholders. Such vision supports start-ups and corporations venturing into circular business models, where economic value includes social and environmental ones [37]. Most of the initiatives reported by the sample are directed to external actors, namely the local community, and companies' stakeholders. Although the employment potential role is significant in CE, the initiatives implemented are rarely translated into the creation of new jobs, in contrast with the literature [74, 48]. Companies tend to focus solely on the positive impacts of their social initiatives, emphasizing win-win situations but underestimating the possible tensions e.g., due to conflicting stakeholders' interests. As pointed out by [59], the relationships between resource circularity and social value can have negative repercussions but companies often ignore such aspects. For this reason, it is urgent to deeply analyse the social aspect and understand how the CE can overcome these repercussions. The polarization may be due to the lack of conceptualization. The boundaries of the social construct are still blurred, and this may hamper companies' adoption of social CE practices clarity [54]. Interesting is the position of consumers, as they are considered relevant actors in the transition to CE but are often perceived as passive and resistant to change [40]. In this sense, involving consumers in the company's CE initiatives would be relevant to promote customer loyalty and raise awareness on CE-related topics [48]. Further work is needed to find the most appropriate way to communicate to consumers a link between the concept and policies of the CE and the food industry.

At the same time, CE has an undoubted financial impact on companies. Relevant financial gains are linked to improved efficiency. The cost is relevant, but the positive trade-off is also considerable and often embedded in marketing strategies that increase brand value. However, CE cost is the biggest financial barrier in the sample. Moreover, the size of the company affects the viability of CE. SMEs, which largely represent the Portuguese AFS

[46], have more costs due to limited scale gains [31]. The assessment follows ordinary financial tools, a tendency already observed [38]. One exception is the sustainability dashboard created to drive companies' investments towards the three pillars of sustainability. Their example evidenced considerable issues regarding the company's internal communication. Employees in the financial sector often struggle to include circular logic in financial planning and measurement due to poor communication between departments. This generates an information gap which fuels the cultural issue. Despite market and liquidity reasons pushing companies to consider the short-term horizon, it is crucial to combine short- and long-term perspectives. Circularity involves a longer period, thus only a long-term perspective can fairly represent related financial benefits [38]. The uncertainty found during the interviews should be interpreted critically. Linear investments also entail market and environmental risks, while CE provides a considerable competitive advantage in the long term [3]. Again, the point is cultural: companies want to keep what they are already doing or want to invest in something different that will probably have a lower return in the short term but with long-term potential. Companies need a strategic approach to CE, the financial variable must be embedded and interpreted within a broader business plan that has a clear medium- and long-term objectives. A partial or incorrect financial evaluation does not allow companies to communicate the value of their activities, limiting the quantity and quality of financial resources they could obtain from investors or the banking system. Policy interventions are hardly mentioned in the sample, although they are crucial drivers of financial incentives. In Europe, there are already various forms of supply and demand-side incentives (e.g., in terms of taxation and subsidies) for circular eco-innovation to support companies, especially SMEs, in the transition to CE [14].

Overall, the need to measure and communicate the financial impact of CE [31, 38]. has become more and more urgent with the introduction of measures such as the 'Taxonomy Regulation' in Europe [21], and the Corporate Sustainability Reporting Directive (CSRD) [20]. Although there was not a specific focus on CE in previous reporting standards, sustainability reporting has evolved over the years [22], making CE one of the environmental objectives of the new directive [20]. Such interventions force companies to start preparing to meet the upcoming requirements. Such preparation will be challenging, especially for SMEs, given their limited reporting experience [22]. Within this context, the new ISO 59000 series will facilitate the sustainability and traceability of economic activities, potentially guiding organizations interested in the performance of companies adopting the requirements, like financial institutions and governments [34].

The AFS plays a crucial role in the global and Portuguese economy. The demand for sustainable investments in the sector is increasing; this may contribute to establishing more sustainable practices in the long run [22]. Finding ways to measure and communicate the CE practices and investments made it crucial to comprehend internally the strategic scope of the implemented practices and to overcome the limitations of scarce financial resources by providing accurate information to attract financial capital.

The choice of a single Country might have affected the results, so findings should be generalised with caution. However, Portuguese AFS centrality as well as the interest shown in CE in the sector make it a valuable case study for the aim of the analysis. Moreover, the limited number of responses is possibly due to the research strategy adopted, which allowed the identification of companies with a good level of knowledge on the topic, obtaining more substantiated answers during the interviews.

Studies on identifying company needs and capabilities towards CE are encouraged in the sector to gain more knowledge on the topic and support the design of assessment approaches that address business reality, namely in other EU countries, to study cross-cultural differences. Further studies on the impact of CE on companies' FP are recommended, especially for defining monitoring tools adequate to communicate CE's potential. Finally, more attention is required on social value creation and financial performance and how can be better integrated into CE and specifically on its conceptualization.

6 Conclusions

The present article based on nine interviews conducted on a selected sample of Portuguese companies of the AFS adopting circularity principles and identified through a previous survey, offers an overview of the status of CE in a European AFS context. Portugal was selected thanks to the relevance of the AFS, as well as the numerous initiatives to promote CE in the Country. Empirical evidence was collected through an explorative survey and subsequent semi-systematic interviews with companies already adopting CE practices and principles in their activities. The survey showed that CE is increasingly perceived as a holistic approach, despite the environmental perspective is still prevalent. Companies largely retrace the circular practices implemented to incremental innovation, being limitedly aware of the boundaries between innovative and conventional measures. Circularity assessment is limited; however, several companies already adopted assessment tools which potentially address circularity, revealing a low level of interest or awareness in the assessment. The companies interviewed engage CE to limit environmental damage but also to generate revenues, however cultural and financial factors hamper its uptake in the sector. Measurement is limited in the sample and often perceived as a secondary objective, although it is fundamental to ensure effective implementation of CE. CE generates social value through employment and commitment to the community. This is translated mainly into services for the community, attention to the employee's well-being, and the development of collaborative networks. Finally, Financial performance is a barrier but also a potential driver for CE implementation. Companies' capacity to valorise circular-related investments and to communicate their financial value broaden their financing options, making CE part of the company resilience strategy. Overall, company size affects the capacity to implement and measure circularity. SMEs and micro companies have limited impact on the market; measuring and communicating the circular value created allows them to gain resources to further orient their business to sustainability. The study, although exploratory and based on a reduced sample of companies, provides interesting insights on how CE can generate social value in the AFS, as well as contributing to understand the relationship between circularity and companies FP Promoting sustainable production and consumption in the sector will have a cascading effect on society, and the CE is a valuable tool for pursuing this path.

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Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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1.1 Supplementary materials

Table S1 Survey design stages and references

Section	RSQs	Topic	Aim	Reference
A		• Location	Collecting general information regarding the company and the respondent to map the sample.	
		• Size		
		• Supply chain type		Van der Vorst et al. (2007)
		• Supply chain stage		Stone and Rahimifard (2018); Nosratabadi et al. (2020); Wunderlich (2021)
		• Job position of the respondent		Walker et al. (2022)
B	2, 3	• Sustainable development	Understanding the awareness level regarding SD. It is relevant to assess so for later clarify the relations with CE and better understand its features.	Geissdoerfer et al. (2017); Baker (2005)
		• Circular Economy	Comprehending the awareness level regarding CE. This enables to better define the sample, including only companies that are familiar with the concept.	Ghisellini et al. (2016); Kohornen et al. (2018)
		• Circular Economy characterization	Understanding the most important CE's features and shedding light on the connection between CE and SD. Given the lack of a unique definition, it is relevant to capture how the concept is perceived by the respondents.	Walker et al. (2022)
		• Relationship between Circular Economy and Sustainable Development		
C	1	• Circular economy practices characteristics	Identifying companies that have already adopted or that are adopting circular practices.	Rotolo et al. (2022)
			Characteristics of the CE practices, focusing on the principles adopted.	
			Assessing circularity's level by associating the practice implemented to the R framework.	Potting et al. (2017); EC, (2008)
			The question allows to frame the circular processes implemented by the companies.	Scandurra et al. (2023)
			Defining the sector's maturity level regarding circularity.	Scandurra et al. (2023)
			Analysing the nature of the innovation and characterize in detail the maturity of the sector.	Scandurra et al. (2023)
		• Practices assessment	Defining the assessment methods adopted by companies.	Roos Lindgreen et al. (2022)

1.2 Survey questions

Table S2 Survey questions: English version.

If you agree to participate voluntarily, please tick the box below. I have understood the procedures described above. I agree to participate in this study and authorise the information collected to be published for scientific purposes.	Informed consent declaration.
Section 1 General information about the company and the respondent-This preliminary section allows us to classify companies per region, size, supply chain type and stage, but also to evaluate some basic characteristics of the respondent.	
1.1 Where is it located? • North. • Centre. • Lisbon Metropolitan Region. • Alentejo. • Algarve.	
1.2 Which size is it? (Employees) • Micro (1-9). • Small (10-49). • Medium (50-249). • Large (>250).	
1.3 In which type of supply chain is it involved? • Agri-food chains for fresh products (e.g., vegetables, fruits, or animals). Please specify which…. • Agri-food chains for processed food products (e.g., portioned meat, snacks, juices, and canned food products) Please specify which… • Agri-food chains for processed products used as raw materials for other chains that are further processed (1st, 2nd processing). Please specify which…	Van der Vorst, J. G. A. J., da Silva, C. A. and Trienekens, J. H. (2007) *Agro-Industri Supply Chain: concepts and applications, Agricultural Management, Marketing and Finance. Occasional Paper*. 17. Rome. Available at: http://www.fao.org/3/a-a1369e.pdf
1.4 If fresh food products, please indicate which (e.g. tomato, ...)	
1.5 If processed food products, please indicate which (e.g. cheese)	
1.6 If processed agri-food products used as raw materials for other additional processing chains, please indicate which (e.g. fruit preparations)	
1.7 What stage of supply chain is it involved? • Primary production • Handling and storage • Processing and packaging • Distribution • Retailing	Stone, J., & Rahimifard, S. (2018). Resilience in agri-food supply chains: a critical analysis of the literature and synthesis of a novel framework. Supply Chain Management: An International Journal.

• Consumption • End of life (e.g., wasted food oil, food waste, wastewater) • Whole supply chain	Nosratabadi, S., Mosavi, A., & Lakner, Z. (2020). Food supply chain and business model innovation. Foods, 9(2), 132. Wunderlich, S. M. (2021). Food supply chain during pandemic: changes in food production, food loss and waste. International Journal of Environmental Impacts, 4(2), 101-112.
1.8 Job position of the respondent? • General management • Marketing and sales • Research and development • Production • Sustainability and CSR • Other (please specify……….)	The present question of the survey was adopted by the study of Walker et al. (2022), who explored frontrunners companies adopting CE's practices.
Section 2 Analysis of company's awareness of CE and SD- This section allows us to test the respondent's level of awareness regarding both SD and CE, it enables to deep dive into the topic thanks to a combined approach given by closed multiple questions and ranking questions, adopting the Likert scale technique.	
2.1 What does Sustainable Development mean, for you? Please indicate your level of agreement with each of the following statements. (Strongly disagree, disagree, neither agree nor disagree, agree, strongly agree). • A transformation that ensures the present and future security and well-being of human's living conditions, (Geissdoerfer et al. 2017)-Social oriented • "The balanced and systemic integration of intra and intergenerational economic, social, and environmental performance" (Geissdoerfer et al. 2017)-Systemic oriented • A system in which the economy is less resource and energy intensive but more equitable in its impact (Baker, 2005)-Economic oriented • A system in which "human activity is conducted in a way that conserves the functions of the earth's ecosystems" (Geissdoerfer et al. 2017)-Environment oriented	The idea was to understand if the respondent companies are aware of SD. It is relevant to assess so for later clarify the relations with CE and better understand its features. The present section of the survey was adopted by the study of Van Langen et al. (2021), who explored the perception and awareness of CE among different stakeholders.

• Other meanings (please indicate yours…………….) • I don't know	
2.2 What does Circular Economy mean, for you? Please indicate your level of agreement with each of the following statements. (Strongly disagree, disagree, neither agree nor disagree, agree, strongly agree). • A system that decouples economic growth from virgin resource use, encouraging innovation, increasing growth, and creating more employment-(EMAF, 2015) Economic oriented. • A regenerative system in which resources, waste, and emissions are reduced by closing, or narrowing material and energy loops (Ghisellini et al., 2016)-Environment oriented. • A system based on a societal production-consumption model that maximizes the output produced by using cyclical materials flows, but also limits the outflows to a level tolerates by the biosphere and includes the ecosystem in economic cycles (Korhonen et al., 2018) –Systemic oriented. • An economy based on sharing instead of owning, collaborative and participative decision-making, and more efficient use of resources through a cooperative vision (Korhonen et al., 2018) – Social oriented. • Other meanings (please indicate yours…………….). I don't know.	The aim was to comprehend first if the respondent companies are familiar with CE. this enables to better define the sample, including only companies that are familiar with the term.
2.3 According to your understanding, which statements below characterize circular economy? Please assign a level of importance to each statement regarding the circular economy. (Characteristic not important at all, slightly important, moderately important, very important, extremely important). • During the life cycle of a product, materials are reduced, reused, recycled, or recovered • Goods are produced in a way that enables the maintaining and recovery of value of materials such as gold and other scarce materials	The aim of the present section was to assess the level of awareness of the AFS regarding CE. The question enables to understand which are the most important CE's features according to AFS's companies. Given the lack of a unique definition, it is relevant to capture how the concept is perceived by the respondents. The present section of the survey was adopted by the study of Walker et al. (2022), who explored frontrunners companies adopting CE's practices.

• Goods are produced, or services are provided in a way that increases their durability, before they are disposed • Products are designed in a way that eliminates waste, because after their end of life, they re-enter the value chain as material input • Businesses offer a service to users, instead of selling their products to customers (e.g., renting a car, instead of selling it) • More goods and services are produced while causing fewer negative impacts on the environment • More goods and services are produced while using fewer material resources or energy Other, please specify:	
2.4 If you answered VERY IMPORTANT or EXTREMELY IMPORTANT under "Other meanings" to the previous question, please specify which	
2.5 In your opinion, what kind of effect does the circular economy have on the three sustainability pillars **(Environment, society and economy)?** Please indicate your level of agreement with each of the following statements. (Strongly disagree, disagree, neither agree nor disagree, agree, strongly agree). • The circular economy is one of the tools that will help achieve the UN sustainable development goals • The circular economy is the main tool to achieve the UN sustainable development goals • The circular economy increases the economic profitability of a company • The circular economy improves the environmental performance of company • The circular economy increases social benefits for employees and other stakeholders The circular economy increases social equality along the company's value chain	The objective of the question was to shed light on how the AFS perceives the connection between CE and SD. The literature has confirmed that the two concepts have different touchpoints but also differences (Geissdoerfer et al., 2017; Korhonen et al., 2018; Murray et al., 2017), thus it is relevant to understand how practitioners of the sector perceive such relation. The present section of the survey was adopted by the study of Walker et al. (2022), who explored frontrunners companies adopting CE's practices.
2.6 If you answered VERY IMPORTANT or EXTREMELY IMPORTANT under "Other meanings" to the previous question, please specify which	
Section 3	

<table>
<tr><td colspan="2">Agri-food companies - The present section of the survey was oriented to identify and analyze the circular practices implemented by the sector's companies.</td></tr>
<tr><td>3.1 Has your company already developed or is developing actions linked to a concept of circularity? (1 answer)
• Yes, fully implemented
• Yes, partially implemented with some ongoing implementations areas
• Yes, partially with no additional applications foreseen in the near future
• First implementation ongoing
• No implementation, but some foreseen in the near future
• No implementation and no related activity foreseen in a near future
• I don't know
• Other</td><td>The question allows to identify those companies that have already adopted or that are adopting circular practices. The present question of the survey was adopted by the study of Rotolo et al. (2022), which analyzed the perception of CE in the AFS in Argentina.</td></tr>
<tr><td>3.2 Could you describe such practices?</td><td>Open question</td></tr>
<tr><td>3.3 To which circular principles are linked?
Check-all-that-apply
• Emission reduction
• Renewable energy use
• Design to extend product's life
• Systems to recover (valorize) waste, by-products, or raw materials
• Other (Specify)
I don't know</td><td>The question allows to dive deeper into the characteristics of the practices, focusing on the CE principles adopted. The present question of the survey was adopted by the study of Rotolo et al. (2022).</td></tr>
<tr><td>• 3.4 To which strategies of the 4Rs frameworks are linked? (Check-all-that-apply)
• Reduce (e.g., exchange of agricultural inputs, or food donation)
• Reuse (e.g., direct reuse of organic residues for animal feed, or composting)</td><td>The idea was to assess circularity's level by associating the practice implemented to the R framework. In literature Potting et al. (2017) defines the level of circularity according to the 9Rs framework, the present survey opted for the 4Rs in line with the European waste framework[2] (EC,</td></tr>
</table>

[2] By "reduce" is meant 'Prevention': All the "measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the re-use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of harmful substances in materials and products". By "reuse" is meant 'Preparing for re-use', namely "checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing". By "recycle" is meant "any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations". By "recover" is meant "any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a

• Recycle (e.g., Meat residues protein portion reprocesses into pet food, or wasted oil reprocesses into detergent) • Recover (e.g., organic residues reprocess into biogas though anaerobic digestion, or production of agro-pellet from straw) • None • I don't know	2008- Available at: http://data.europa.eu/eli/dir/2008/98/oj)
• 3.5 How would you classify the circular processes implemented by your company? (Check-all-that-apply) • Optimization of the production process- in terms of materials, energy, or technology use. • Sharing of resources- tangible and intangible resources. • Reprocessing- any operation/ process by which waste food is reprocessed into fuel/energy/raw materials/value-added products • Incineration and Landfilling- Waste disposal on landfills or incineration with or without biogas recovery. • Other…………….(please describe)	The question allows to frame the circular processes implemented by the companies. The classification is based on (Scandurra et al. 2023).
3.6 How would you define the company practices implemented in terms of innovativeness? (1 answer) • Conventional - well-established techniques and technologies like anaerobic digestion, inter-cropping, crop rotation, cover cropping, traditional organic composting, etc… • Incrementally innovative (improvement of an existing practice) - productivity-oriented innovations aimed at improving resource-efficiency. • Radically innovative (a completely new practice, not existing before)- products that render the existing ones non-competitive, creating also new knowledge. • None I don't know	The aim was to define the sector's maturity level regarding circularity. The classification is based on (Scandurra et al. 2023).
3.7 If innovative (conventional, incremental and/or radically), how would you consider the perspective of such innovation? (1 answer)	The question enables to deep dive into the nature of the innovation and characterize in detail the maturity of

particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy.

• Socio-organizational – if the aim is to promote different habits and mindsets. • Technological – if the aim is to use technology to generate different products or services • None I don't know	the sector. The present classification is based on (Scandurra et al. 2023).
3.8 Does your company measure circular practice's impact? (1 answer) • Yes • No • Partially • I don't know Other (Specify)	
3.9 If you answered YES to the previous question, how does your company measures circularity? - If you answered NO, please indicate "not applicable • Life cycle based/footprint • Reporting framework • Tailor-made indicators • Single indicators • Other (Specify) Not applicable	The question allows to define a first classification of the methods adopted by companies. The present classification was adopted by the work of Roos Lindgreen et al. (2022).
3.10 Could you give us more details about the method used?	Open question
3.11 I would be available to be subsequently contacted for future interviews, related to this topic of Circular Economy practices in the agri-food sector and linkage with the financial sector.... • Yes • No	

Table S3 Survey questions: Portuguese version.

Se concordar em participar voluntariamente, por favor assinale a opção abaixo.	Compreendi os procedimentos descritos acima. Concordo em participar neste estudo e autorizo que a informação recolhida seja publicada para fins científicos.
Secção 1 Informação geral: Empresa e Participante - Esta secção preliminar visa classificar as empresas por região, dimensão, tipo de cadeia de abastecimento e fase da cadeia, bem como avaliar algumas características básicas do inquirido.	
1.1 Identifique, por favor, onde está localizada a sua empresa?	• Norte • Centro

	• Área Metropolitana de Lisboa • Alentejo • Algarve
1.2 Identifique, por favor, qual é a dimensão da sua empresa (em função do número de funcionários)?	• Micro (1-9) • Pequena (10-49) • Média (50-249) • Grande (>250)
1.3 Identifique, por favor, a tipologia de cadeia de abastecimento agroalimentar em que a sua empresa está envolvida?	• Produtos alimentares frescos (por exemplo, vegetais, frutas, carne ou peixe) • Produtos alimentares processados (por exemplo, snacks, sumos ou produtos alimentares enlatados) • Produtos alimentares processados utilizados como matérias-primas para outras cadeias que se processam adicionalmente (, por exemplo, preparados de fruta, extratos proteicos).
1.4 Se produtos alimentares frescos, por favor, indicar qual (por exemplo: tomate	
1.5 Se produtos alimentares processados, por favor, indicar qual (por exemplo: queijo)	
1.6 Se produtos agroalimentares processados utilizados como matérias-primas para outras cadeias que se processam adicionalmente, por favor, indicar qual (por exemplo: preparados de fruta)	
1.7 Indicar, por favor, em que fase/ fases da cadeia de abastecimento agroalimentar trabalha a sua empresa?	• Produção primária • Manipulação e armazenamento • Processamento e embalagem • Distribuição alimentar • Retalho alimentar (• Hotelaria, restauração e cafetaria • Reciclagem e tratamento de resíduos
1.8 Indique, por favor, em que área/departamento da empresa trabalha?	• Gestão • Marketing e vendas • Investigação e desenvolvimento • Produção • Sustentabilidade e responsabilidade social • Outros
Secção 2 Nível de conhecimento - Esta secção visa avaliar os conhecimentos relativos ao Desenvolvimento Sustentável e Economia Circular.	

2.1 Na sua opinião, indique, por favor, qual das seguintes declarações define melhor o desenvolvimento sustentável?	• Uma transformação que garanta a segurança e o bem-estar atual e futuro das condições de vida do ser humano (orientação social) • A integração equilibrada e sistémica do desempenho económico, social e ambiental intra e intergeracional (orientada para o sistema) • Um sistema em que a economia é menos intensiva em recursos e energia e mais equitativa no seu impacto (orientado para a economia) • Um sistema em que a actividade humana é conduzida de uma forma que conserve as funções dos ecossistemas da Terra (orientado para o ambiente) • Não sei • Outros
2.2 Na sua opinião, indique por favor, qual das seguintes afirmações define melhor a Economia Circular?	• Um sistema que dissocia o crescimento económico da utilização de recursos naturais, encorajando a inovação, aumentando o crescimento, e criando mais emprego (orientado para a economia) • Um sistema regenerativo no qual os recursos, os resíduos e as emissões são reduzidos através do fecho, ou do estreitamento dos ciclos de utilização de energia e de materiais (orientado para o ambiente) • Um sistema baseado num modelo societal de produção-consumo que maximiza o rendimento produzido pela utilização de fluxos cíclicos de materiais, mas também limita os fluxos de saída a um nível tolerado pela biosfera e inclui o ecossistema nos ciclos económicos (orientado para o sistema) • Uma economia baseada na partilha em vez da posse, na colaboração e na tomada de decisões participativas, e numa utilização mais eficiente dos recursos através de uma visão cooperativa (orientada para a sociedade) • Não sei • Outros

2.3 De acordo com o seu entendimento, que afirmações abaixo caracterizam a economia circular? **Por favor atribua um nível de importância a cada declaração relativa à economia circular.** **(Característica nada importante, ligeiramente importante, moderadamente importante, muito importante, extremamente importante).**	• Durante o ciclo de vida de um produto, os materiais são reduzidos, reutilizados, reciclados, ou recuperados • Os bens são produzidos de forma a permitir a manutenção e recuperação do valor de materiais como o ouro e outros materiais escassos • Os bens são produzidos, ou os serviços são fornecidos de uma forma que aumenta a sua durabilidade, antes de serem eliminados • Os produtos são concebidos de forma a eliminar o desperdício, porque após o seu fim de vida, voltam a entrar na cadeia de valor como matéria-prima alternativa • As empresas oferecem um serviço aos utilizadores, em vez de venderem os seus produtos aos clientes (por exemplo, alugar um carro, em vez de o venderem) • Mais bens e serviços são produzidos, procurando causar menos impactos negativos sobre o ambiente • Mais bens e serviços são produzidos utilizando menos recursos ou energia • Outros significados
2.4 Se respondeu MUITO IMPORTANTE ou EXTREMEMENTE IMPORTANTE em "Outros significados" à pergunta anterior, por favor especifique quais	
2.5 Na sua opinião, que tipo de efeito tem a economia circular sobre os três pilares da sustentabilidade (Ambiente, Sociedade e Economia)? **Queira indicar o seu nível de concordância com cada uma das seguintes declarações.** **(Discordo totalmente, discordo, não concordo nem discordo, concordo, concordo totalmente).**	• A economia circular é uma das ferramentas que ajudará a alcançar os objectivos de desenvolvimento sustentável das Nações Unidas • A economia circular é o principal instrumento para alcançar os objectivos de desenvolvimento sustentável das Nações Unidas • A economia circular aumenta a rentabilidade económica de uma empresa • A economia circular melhora o desempenho ambiental da empresa • A economia circular aumenta os benefícios sociais para os empregados e outras partes interessadas

	• A economia circular aumenta a igualdade social ao longo da cadeia de valor da empresa
Secção 3 Circularidade: Identificação e Avaliação - A presente secção do inquérito foi orientada para identificar e analisar as práticas circulares implementadas pelas empresas do sector (por exemplo, rotação de culturas, utilização de resíduos orgânicos como fertilizante, processamento de resíduos para obter biogás, reutilização de excedentes alimentares como ração animal, doação de excedentes alimentares para consumo humano, entre outros).	
3.1 A sua empresa já desenvolveu ou está a desenvolver práticas ligadas à circularidade?	Sim, totalmente implementadas Sim, parcialmente implementado com algumas implementações em curso Sim, parcialmente sem aplicações adicionais previstas num futuro próximo Sim, primeira implementação em curso Nenhuma implementação, mas algumas previstas num futuro próximo Nenhuma implementação e nenhuma actividade relacionada prevista num futuro próximo Não sei • Outros
3.2 Poderia descrever tais práticas?	•
3.3 A que princípios circulares estão ligadas essas práticas? Verificar tudo oque se aplica.	• Utilização de energia renovável (por exemplo, biogás gerado por biodigestão de resíduos orgânicos, utilização de energia solar por painéis solares,...) • Concepção para prolongar a vida útil do produto (por exemplo, partilha de *inputs* agrícolas,...) • Sistemas para recuperar (valorizar) resíduos, subprodutos ou matérias-primas (por exemplo, utilização de resíduos orgânicos para produzir fertilizantes, processamento de subprodutos para obter ração animal,...) • Redução de emissões (por exemplo, redução de fertilizantes químicos e pesticidas,...) • Não sei • Outros
3.4 A que estratégias das estruturas dos 4Rs estão ligadas essas práticas? Verificar tudo-que se aplica. Por 4Rs entendemos: Reduzir: as medidas tomadas antes de uma substância se tornar resíduo que visam reduzir a quantidade de resíduos, os impactos adversos desses resíduos ou o	• Reduzir (por exemplo, troca de inputs agrícolas, ou doação de alimentos) • Reutilização (por exemplo, reutilização directa de resíduos orgânicos para alimentação animal, ou compostagem) • Reciclar (por exemplo, porção de proteína de resíduos de carne

conteúdo de substâncias nocivas nos mesmos. **Reutilização: controlo, limpeza ou reparação de operações de recuperação, através das quais produtos ou componentes que se tenham tornado resíduos podem ser reutilizados.** **Reciclagem: qualquer operação de recuperação através da qual os materiais residuais são reprocessados em produtos, materiais ou substâncias, quer para o fim original, quer para outros fins.** **Valorização: qualquer operação através da qual os resíduos servem um propósito útil, substituindo outros materiais que de outra forma teriam sido utilizados para cumprir uma determinada função.**	reprocessada em alimentos para animais de estimação, ou óleo desperdiçado reprocessado em detergente) • Recuperar (por exemplo, reprocessar resíduos orgânicos em biogás através de digestão anaeróbia, ou produção de agro-*pellets* a partir de palha • Nenhum • Não sei
3.5 Como classificaria os processos circulares implementados pela sua empresa? **Verifique tudo-que se aplica.** **A classificação é baseada numa revisão bibliográfica realizada pelos autores do inquérito.**	• Optimização do processo de produção - em termos de materiais, energia, ou utilização de tecnologia (por exemplo, utilização de estrume como fertilizante orgânico, utilização de subproduto do açúcar para a produção de álcool,...) • Partilha de recursos - recursos tangíveis e intangíveis (por exemplo, partilha de *input*s agrícolas como fertilizante, partilha de competências e conhecimentos,...) • Reprocessamento - qualquer operação/processo através do qual os resíduos alimentares são reprocessados em combustível/energia/matérias-primas/produtos de valor acrescentado (por exemplo, geração de biogás através da digestão anaeróbica, reprocessamento de resíduos de carne utilizada como alimento para animais de estimação,...) • Incineração e Aterro - Eliminação de resíduos em aterros ou incineração com ou sem recuperação de biogás (por exemplo, incineração de resíduos alimentares orgânicos para obtenção de biogás, aterro de resíduos,...) • Outros
3.6 Como definiria as práticas da empresa implementadas em termos de inovação?	• Convencional - técnicas e tecnologias bem estabelecidas como a digestão anaeróbica, a inter-culturas, a rotação de culturas, a cultura de cobertura, a

A classificação é baseada numa revisão bibliográfica realizada pelos autores do inquérito.	compostagem biológica tradicional, etc... • Incrementalmente inovadoras (melhoria de uma prática existente) - inovações orientadas para a produtividade com o objectivo de melhorar a eficiência dos recursos. • Radicalmente inovadores (uma prática completamente nova, não existente anteriormente) - produtos que tornam os existentes anteriormente não competitivos, criando também novos conhecimentos. • Nenhum • Não sei
3.7 Se inovador (convencional, incremental e/ou radicalmente), como consideraria a perspectiva de tal inovação?	• Sócio-organizacional - se o objectivo for promover diferentes hábitos e mentalidades. • Tecnológica - se o objectivo for utilizar a tecnologia para gerar diferentes produtos ou serviços • Nenhum • Não sei
3.8 A sua empresa mede o impacto da prática circular?	• Sim • Não • Parcialmente • Não sei • Outros
3.9 Como é que a sua empresa mede a circularidade?	• Baseado no ciclo de vida/ pegada ecológica • Através de relatórios de divulgação/comunicação • Utilizando indicadores específicos • Utilizando indicadores únicos • Outros
3.10 Poderia dar-nos mais pormenores sobre o método utilizado? Por exemplo, Tipologia de avaliação do ciclo de vida, de indicador único, ou tipo de relatórios,...	
3.11 Estaria disponível para ser posteriormente contactado para futuras entrevistas, relacionadas com este tema das práticas de Economia circular no sector agro-alimentar e ligação com o setor financeiro ?	

1.3 Interview guidelines

Drivers for the adoption of CE

1. What was the main driver to introduce CE in your company strategies?

a) Reducing the environmental impact of your activities.
b) Increasing the social value of your activities (e.g., contributing to the well-being of the community).
c) Improving the economic and financial profile of your activities (e.g., Cost reduction and financial profitability).
d) Increasing the prestige- effectively communicate the firms' sustainable strategies (e.g., for improving the relationship with customers and supply chain partners) -(Ormazabal et al. 2018).
e) Ensuring the long-term viability of the company (e.g., guaranteeing the availability and accessibility of resources in the future and allowing the company to conquer new markets- (Ormazabal et al. 2018).
f) All the above.
g) Others. Specify

CE Assessment

2. Why does your company assess circularity? (Roos Lindgreen et al., 2022)
3. If not applicable, why not?
4. If it does assess CE: What benefits does your company get from assessing circularity?
5. If it does not assess CE: Is the reason for this linked to the characteristics of assessment methodologies available for circular economy or linked with internal capacity (barriers)? (Roos Lindgreen et al., 2022)
6. Which assessment methods does your company use to measure circularity?

a) Life cycle-based methods.
b) Sustainability reporting frameworks, such as Global Reporting Initiative (GRI) Standards.
c) Single indicators.
d) Tailor-made indicators
e) Other….

7. Do you think that the assessment methods you adopt for circularity address also sustainability?
8. Do you think there is a difference between the assessment of circularity and the assessment of sustainability? (Roos Lindgreen et al., 2022)

CE and Social Sustainability

9. Do you think that CE generates social value (e.g., generates social cohesion, inclusion, equality…)?
10. Do you think that the circular strategies implemented in your company generate social value? If yes, how? E.g., promoting social inclusion (connect employees with a distance to the labor market, more diversity), leading people in a neighborhood or region to feel connected to each other (social cohesion), promoting responsible consumption (people will use their products more sustainable) (Quintelier et al. 2023). If not, why?

CE and Financial performance

11. Do you think the CE impacts a company's financial performance? If yes, how? (e.g., by reducing costs due to process efficiency, or by generating more revenues due to access to new markets). If not, why?
12. You have already adopted CE. Did you assess the financial performance value of your CE strategies? If yes, how? (e.g., by measuring the net present value, the internal rate of return, or the payback period, marketing strategy based on customer preferences-(Kanzari et al. 2022)). If not, why?
13. According to you, what are the main barriers in the financial evaluation of CE? (e.g., dealing with longer time horizons compared to linear investments, the uncertainty of the future cashflows, communicating with investors -(Kanzari et al. 2022)).

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Chapter 4: Circularity and Sustainability assessment: Preliminary results from the "Fattoria della piana" case, Italy.

1.1 Introduction

In recent decades, the increase in food demand has led to a considerable development in productivity with significant impacts on the environment and human health. The need to adapt production has pushed the AFS towards industrialised products based on chemical fertilisers and extensive monocultures, which are now responsible for significant CO_2 emissions and massive water consumption (Oliveira et al. 2021).

In this context, dairy products are an essential source of nutrients for human diets, but several studies stress the importance of reducing their intake in European diets to mitigate environmental and health risks (Stanchev et al., 2020). The dairy sector is an example of a complex system, articulated in a combination of demand and supply segments, comprising fodder production, breeding, production, distribution, retailing and consumption (Oliveira et al., 2021; Stanchev et al., 2020). In particular, the Italian dairy sector is known for its high quality and variety, which is protected and regulated by a system of designations of origin (e.g. PDO, PGI) and rooted in the Mediterranean diet, a culinary as well as a cultural model (Oliveira et al. 2021).

Nowadays, the sector contributes to severe environmental challenges, e.g., due to improper manure and sewage management, which contribute to climate change, eutrophication, acidification of ecosystems, and damage to biodiversity, also impacting human health (Zhang et al. 2021). Thus, to develop a sustainable value chain for the sector, it is necessary to consider the environmental impact along the whole supply chain (Stanchev et al., 2020).

In this context, CE has emerged as a paradigm able to overcome the so-called linear "take-make-dispose" approach (Santagata et al., 2021). Interestingly, the principles of circularity are already present in traditional dairy production systems, e.g. waste to waste-to-energy solutions based on cattle manure (Kilik and Kilik, 2017). Despite several studies exploring CE in the dairy context, there are still relevant challenges before achieving the circularity of nutrients, carbon, and waste in the sector (Stanchev et al., 2020). Focusing on single principles may indeed hinder severe trade-offs. Circular does not imply sustainability as risks of burden shifting to other production stages exist (Samani 2023). Thus, it is relevant to check if the circular strategies implemented are aligned with sustainability (Luthin et al., 2023).

In this sense, a quantitative and comprehensive assessment is a crucial step to verify the capacity of a circular strategy to reduce the environmental, economic, and social impacts of a given system. Efficient circularity indicators should help managers and entrepreneurs to track the organization's performance, supporting their decision-making. However, often companies have difficulty understanding how indicators impact the efficiency of their practices, limiting their informative potential (Kounani et al., 2023). In this sense, the lack of shared standards for CE assessment further limits its implementation at the company level (Roos Lindgreen et al., 2022). Indeed, aware of this lack, the ISO is working on the standardization in the field of CE within the technical committee ISO/TC 323 on "Circular Economy". Among the standard under development within the ISO/TC323 also one focused on "Measuring and assessing circularity performance" (ISO/FDIS 59020). On the contrary, in Italy, the UNI already published the standard UNI/TS 11820; it indicates a set of indicators to measure the circularity level of an organization (UNI/TS 11820:2022). However, it is not sector specific. Thus, finding circularity metrics is still particularly challenging for the AFS, where production and consumption are based on organic materials, which dissolve after use (Moller et al., 2023).

For this reason, recently, some studies focused on the identification of circularity indicators specifically tailored for the AFS (Poponi et al., 2022; Silvestri et al., 2022; Kounani et al., 2023). But, despite the various options available for companies, CE assessment is limited in the AFS (Coluccia et al., 2023).

Moreover, tackling circularity using single indicators exposes to incurring possible distortions (Poponi et al., 2022). A Circular practice is not automatically environmentally sustainable, e.g., the energy demand for recycling certain materials may offset any environmental gains due to avoided extraction of new raw materials. Thus, circularity metrics should be able to assess the environmental performance, besides the level of circularity (Kounani et al., 2023). Hence emerges the importance of empirical studies applying these metrics to verify which instruments effectively support companies in monitoring the circularity and sustainability performance of their strategies (Kounani et al., 2023).

In this context, a significant body of research explored the adoption of methodologies based on the combined use of LCA with circularity indicators (Rigamonti and Mancini, 2021).

Examples in the AFS are Rufí-Salís et al. (2021) which adopted the Material Circularity Indicator (MCI) and LCA to evaluate the environmental and circular impact of an urban agriculture system. Niero and Kalbar (2019) proposed an approach which combined LCA with different types of CE indicators via MCDA and apply it to the beer packaging. In the dairy sector, Gallo et al. (2023) suggested modifying the MCI to suit biological materials better and combined with LCA, applying it in a multiple case study These combined approaches allow to assess the level of circularity of a strategy but also the environmental impacts associated, effectively supporting companies in decision-making (Rigamonti and Mancini, 2021). In this context, the present chapter analyses the case study of the dairy cooperative *Fattoria della Piana*, a relevant example of circularity and industrial symbiosis located in the South of Italy. In 2023, the cooperative was awarded for the 'environmental sustainability' of its business activities in the initiative *Impresa sostenibile*, developed at the national level by the Sole 24 Ore, making the cooperative a best case at the country level. Moreover, the collaboration with the Fattoria della Piana took place as part of a six-month internship within PON No. 2, which enabled primary data to be collected through questionnaires and interviews, improving the overall reliability of the analysis. The heart of the circular ecosystem is represented by the AD-CHP plant, which connects the cooperative with other local businesses, closing the loop of waste and resources. The AD-CHP plant generates symbiotic relationships with both the company's supply chains and with neighboring companies, transforming their waste into inputs for the digester; this, in turn, generates electricity for the national grid, thermal energy for the Fattoria della Piana’s cheese factory and organic fertilizer that is used internally but also redistributed to the companies that deliver waste. This allows partner companies to avoid the disposal of organic waste such as sewage, olive pomace or citrus pulp and, at the same time, to receive organic fertilizer, decreasing dependence on chemical fertilizers. To understand and quantify the environmental benefits of using an AD-CHP plant in a circular perspective, the research question is therefore: *How can companies of the AFS assess and monitor the circularity and sustainability of their* *activities?* The objective of the analysis is to provide a general overview of the cooperative activities through an assessment of the potential environmental impact of the best practices.

1.2 System description-Fattoria della piana

1.2.1 The Structure

Fattoria della Piana, established in 1936, is a cooperative that today covers all activities in the dairy chain, having as final product sheep, goat and cow cheeses. It is the largest farm in the province of Reggio Calabria and one of the largest in southern Italy. The cooperative has incorporated the principles of circularity, setting up a system of symbiotic exchanges to give new life to waste and scrap as resources. The system of symbiotic exchanges starts upstream with the agricultural phase; the farm produces directly in-house a large part of the feed for the breeding phase, using the digestate obtained from the anaerobic digestion plant as a biological fertilizer, returning all the necessary nutrients to the soil for quality production. During the breeding phase, milk is produced for the dairy, but at the same time, waste elements such as manure and slurry are produced and used as input in the digestion plant. In addition, the photovoltaic system located above the barn and the dairy powers the entire farm, 400 kW/h, fully integrated on the roof of the stables, inclined at 14° and facing SOUTH, covering an area of 1,080 square meters, improving the environmental and economic profile of the cooperative (https://fattoriadellapiana.it/). The dairy then uses the milk produced internally, together with the sheep and goat milk contributed by the Calabrian shepherd members to produce various types of cheese. The heat used internally comes from the cogeneration plant fed by the digester. The dairy, in turn, contributes to the digester's activity by supplying whey, while wastewater is directed to the phyto-purification plant located near the farm. Through the anaerobic digestion plant, Fattoria della Piana succeeds in generating a self-sufficient ecosystem capable of transforming the many wastes produced in the various supply chains into resources. In addition, the company collects additional waste from neighbouring companies. This has generated a cycle of symbiotic exchanges and networking opportunities with local companies that allows producers the opportunity to dispose of waste that was a high cost and a huge problem for them, receiving organic fertiliser in return. The main fluxes of material and waste are represented in figure 1.

The cooperative consists of four companies: Fattoria della Piana, owner of the cheese factory, one of the biogas plants and part of the distribution; Uliva, owner of the breeding and fodder production activity and of one of biogas plants; Pastori Calabresi, a cooperative composed of about 90 shepherds and some agricultural producers of olives and citrus fruits; finally, Arriva fresco, which deals with the distribution of the dairy products.

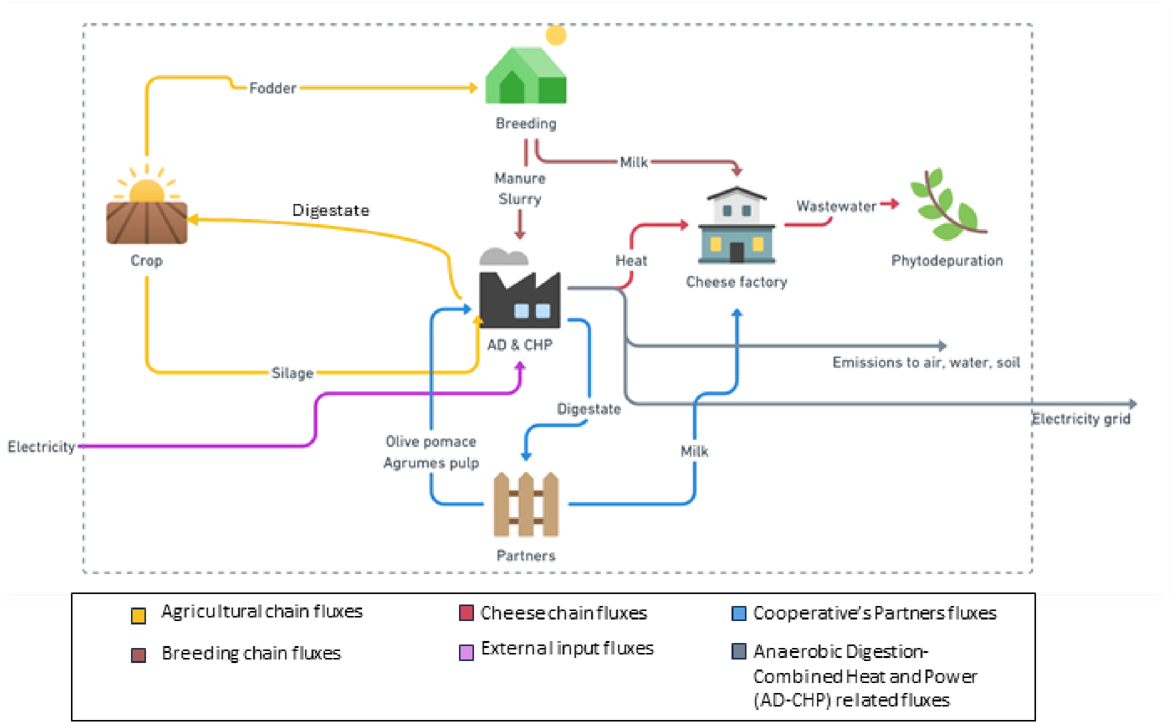

Figure 1 Overview of the main fluxes between the cooperative supply chains and the partners. Source: author's elaboration from data collected at "Fattoria della Piana".

1.2.2 The supply chains

The present section illustrates in detail the various supply chains that characterize the cooperative Fattoria della Piana. All data presented here were collected on site through questionnaire and interviews with managers and other employees of the cooperative.

1.2.2.1 Agricultural chain

The overall 314 ha of cultivated areas (123 corn, 69 sorghum, 87 wheat, 12 ryegrass, 23 alfa-alfa - ha) produced 4,233 tons of corn, 1,442 of sorghum, 1,606 of wheat, 26 of ryegrass, and 124 of alfa-alfa (each 5 years) in 2022. The company acquires externally the seeds, the geodisinfestant and the herbicide (the latter two only used in corn cultivation). No external fertilizer is acquired, since the company uses part of the liquid and solid digestate produced during the anaerobic digestion (around 71% of the total produced) as organic fertilizer. Once the crop is harvested, it is used as fodder in the cow breeding phase. The waste from corn and wheat silage is then used as input for the two anaerobic digestion plants.

1.2.2.2 Breeding chain

The livestock is localized in a shed. The cow breeding consists of 954 cattle (859 Friesian, 95 Brune Alpine-units), almost all of which are dairy cows and only very few animals for slaughter, which happens outside the company. The intensive cow breeding produced 4,869.384 kg of milk in 2022. In terms of diet, the cows are fed with the fodder produced at the farm, while a portion of feeds and supplements is industrially produced and purchased by the company to ensure a weighted nutritional balance. The daily nutrition ratio varies based on the lactation period and the phases of cattle growth. The energy needs of the breeding phase are covered by the national grid and by the solar panel system on the roof of the shed system. The milking takes place using eight automatic milking robots. Afterwards, manure and slurry are scraped through an automated system (collected every 3 hours to avoid methane losses) and gathered via a pumping system that sends them directly to the digestion plant where they are used as inputs, together with animal bedding residues.

1.2.2.3 Cheese production chain

At the cheese factory, the main input is milk; cow milk is mainly produced internally, but a small portion is purchased externally, while a fraction of the cow milk is sold on the market. Sheep and goat milk is provided by the partner Pastori Calabresi, 90 shepherds and sheep farmers from Monte Poro, Aspromonte and Sila crotonese, drawing on the centuries-old tradition of sheep farming in the Calabrian mountains. At the production level, milk is transformed into cheese. The main types of cheese produced are i) mature cheeses, ii) pasta filata cheeses and iii) fresh cheeses. Cheese production is articulated into sub-processes:

1. the milk is stored in the four silos and undergoes an analysis of its properties (e.g., presence of antibiotics, contamination with other types of milk, acidity, etc.);
2. this is followed by pasteurization, during which the milk is sterilized by exposure to high temperatures of 72-74 C° (depending on the type/quality of milk);
3. after pasteurization, the centrifugation allows to remove the coarse dirt, and
4. finally, the exchangers direct the milk towards the polyvalent machine for coagulation and agitation (3 machines with regular, 1 with cradle form).

Afterwards, the production is differentiated according to the type of cheese. At the end of the production phase, all organic waste is destined for biogas (e.g., the whey not incorporated into the ricotta production, unsold products, or cream). The wastewater produced during the production phase is sent to the phytodepuration plant close to the company site. The electricity supply is covered by the photovoltaic panels located on the roof of the cheese factory and the electricity grid, while the heat is originated by the CHP plant, thanks to the AD plant that produces the required biogas.

1.2.2.4 Phytodepuration plant

The wastewater is cleansed by a phytodepuration plant, having a population equivalent of 1,667. Phyto-purification is a natural purification system for domestic, agricultural and sometimes industrial wastewater that reproduces the self-purification principle typical of aquatic and wetland environments. It is a wet ecosystem where thousands of plants together with various components (animals, microorganisms, soil, solar radiation) contribute to the removal of pollutants, making the water clean and reusable and providing additional biomass for the biogas plant. The adopted plants, Phragmites australis, create a suitable habitat for the growth of bacterial flora which act as main agent of biological purification. The flow rate of the plant constructed, in terms of m^3/day of wastewater treated by the phyto-purification system, is 100. The wastewater discharged comes from the cooperative dairy, the milking parlour, the agritourism restaurant, the guest quarters and the offices. The plant occupies 2,200 square metres of surface area with a total of 10,000 plants. The percentage of abatement of COD is 97%, (Chemical Oxygen Demand), so at the end of the purification cycle, water could potentially be reused for irrigation. Data presented in this sub question were collected from the company website (https://fattoriadellapiana.it/).

1.2.2.5 Distribution chain

Distribution is divided into local markets, i.e. upper Calabria, Reggio Calabria and Sicily, national markets and foreign markets. There are three trucks per day, fuelled by diesel. The lorries leave the goods in the company's warehouses, which are then distributed around by the salesmen. The remaining distribution (via couriers) covers national, European and international territory. At the national level, purchasing is done via e-commerce, at the European level by pallets and at the international level by containers (ship).

1.2.2.6 AD -CHP plants

The AD-CHP system implies two main steps. Fist anaerobic digestion, where microorganisms break down organic material in an oxygen free environment to generate biogas and digestate, a nitrogen-rich fertiliser. Then, the biogas is then transformed into electricity and heat by the Combined Heat and Power (Chowdhury, 2021). The cooperative owns two AD-CHP plants of equal size and capacity (electrical power of 998 kW each). One is owned directly by Fattoria della Piana (plant a)), the other by the company’s member Uliva (plant b)). Both plants receive inputs from the fodder production in terms of silage (wheat and corn), from the breeding, in terms of manure, sewage and animal bedding residue and from cheese production in terms of any type of organic waste. Additionally, the plants are fed with olive pomace, citrus fruits, molasses and chicken manure which are provided by the cooperative associates. All data reported in this section were collected on site. In 2022, a) plant produced 5,342 tons of biogas, 2,779 tons of solid and 31,954 tons of liquid digestate. b) produced, 5,342 tons of biogas, 2,660 tons of solid and 30,594 tons of liquid digestate.

The biogas produced is sent to a combined heat and power (CHP) plant that produces electricity and thermal energy. Thus, the AD process produces the following outputs that allow to close the loop of resources of the company:

- Thermal energy-used in the cheese factory and AD-CHP plant;
- Electricity-sent into the electricity grid;
- Digestate-fertilizer in the internal fodder production, but also redistributed to the contributing associates as fertilizer.

Ex-ante scenario

Before Fattoria della Piana built the anaerobic digestion plants, the symbiotic exchange system did not happen. So, the companies now part of the cooperative's network managed their waste themselves, sending it for treatment, representing a significant cost item for the companies. Main partners produce olive pomace and citrus pulp from waste products, as they are active in the olive and citrus sector, but there are also companies active in poultry livestock. Table 1 illustrates the input used in the AD-CHP plant of both Fattoria della Piana and Uliva. Data were collected on site and refer to 2022. Thus, the cooperative found a solution to the by-product disposal problem for itself and neighbouring industries and farms. Furthermore, before the digestion plants heat and electricity were produced from non-renewable sources and in the agricultural field fertilizer was used instead of digestate.

Table 1 Overview of the waste and residues used as inputs in the two AD-CHP plants classified per category, quantity and distance of the delivering company to the plant site in kilometres. - Source: author's elaboration from data collected at "Fattoria della Piana".

Plant	Input	Quantity	Unit	Distance from the plant (Km)
Fattoria della Piana	Manure	3,200	Ton	Internal (0)
	Slurry	2,000	Ton	Internal (0)
	Whey	7,100	Ton	Internal (0)
	Silage	1,100	Ton	Internal (0)
	Olive pomace	364.69	Ton	135
	Olive pomace	13,171.55	Ton	105
	Olive pomace	8,766.52	Ton	70
	Olive pomace	2,257.49	Ton	30
	Agrumes pulp	4,979.12	Ton	68
	Agrumes pulp	9,292	Ton	70
	Agrumes pulp	36.96	Ton	30
	Chicken manure	2,672.99	Ton	30
	Molasses	245.36	Ton	70
Uliva	Manure	4,106	Ton	Internal (0)
	Slurry	2,546	Ton	Internal (0)
	Silage	3,200	Ton	Internal (0)
	Olive pomace	9,893.15	Ton	70
	Olive pomace	2,623.76	Ton	30
	Olive pomace	1,958.02	Ton	135
	Agrumes pulp	8,554.59	Ton	135
	Agrumes pulp	8,510.17	Ton	68
	Agrumes pulp	3,531.9	Ton	70
	Chicken manure	1,800	Ton	NA
	Molasses	1,053.86	Ton	NA

1.3 Materials and methods

The case study methodology adopted here is used in the social sciences to investigate complex cases (Stake, 2013). This methodology allows to capture the exchanges among the various actors in the context in which they take place (Eisenhardt, Graebner, & Sonenshein, 2016). Moreover, a case study, providing exemplary contexts, facilitates the characterization of both theory and practice (Parker and Northcott, 2016). Data were primarily collected by the author on-site through questionnaires and interviews with employees and the management of the cooperative. Additional data regarding the company's structure was sourced from the cooperative website, while background and missing data (related to the LCA modelling) were sourced from existent scientific literature and databases (more detail is presented in Table 3).

1.3.1 The AD process

The principal product of the AD process is biogas. It has an average methane content of 55% for biogas volume. The remaining biogas is assumed to be composed only of CO_2 (Giuntoli et al., 2017). However, a limited portion of the biogas produced is lost and thus released into the atmosphere. In particular, the plant owners' estimates that uncontrolled emissions account for >5% for yield biogas. The AD process also digestate, a co-product in AD plants. The digestate is extracted from the digester, stored in open tanks, and then directly used as organic fertilizer without further treatments (Cusenza et al., 2021). The open storage of digestate causes Nitrous oxide (N_2O) and methane (CH_4) emissions due to the residual organic matter content. The emissions reference data are taken from the literature (Fusi et al., 2016; Reichhalter et al., 2011). Moreover, the system expansion allows to include the credits related to the avoided production and use of the mineral fertilizer (mainly, urea). Thus, in line with Lijó et al. (2014), the mineral fertilizer is substituted as a function of the nutrients contained in the digestate. Finally, the corresponding emissions of the avoided conventional management of 1 ton of animal sewage and manure, as suggested by (Reichhalter et al., 2011; Sedorovich et al., 2007), are 4.10 kg of CH_4 and 0.10 kg of N_2O perm3 in a year.

1.3.2 Combined heat and power (CHP) generation process

The CHP plant generates both thermal and electric energy for which the detailed inventory data are considered. The CHP plant emissions caused by the combustion process are based on secondary data. In particular, the following macro-pollutants are considered in the elaboration: nitrogen oxides and methane.

1.3.3 Circularity indicators: selection

To assess the closed-loop pathways implemented by the company, this study proposes a methodological approach based on LCA methodology and circularity performance indicators. The former allows the assessment of the potential environmental benefits associated with the CE strategies implemented by the company in relation to the biogas plant and the materials used, and then the evaluation of the circularity rate associated with the system. The focus on LCA is motivated by the fact that it is considered a valuable tool to support the assessment of the performance CE strategies in terms of sustainability (Pena et al., 2021). LCA is a science-based method, standardized by the ISO series 14040 and 14044, which evaluates the potential environmental impacts associated with a product, process, or service along its whole life cycle (Roos Lindgreen et al., 2021). LCA can provide useful insights into the potential impacts of upstream and downstream flows related to products or processes, contributing to developing more sustainable circularity strategies (Samani et al., 2023). Circularity performance indicators, on the contrary, measure the ability of a system to conserve the quantity and quality of a material (Rigamonti and Mancini, 2021). The findings here presented results from a preliminary study which applied the mixed method approach given by LCA and circularity indicators with a limited scope to assess the performance of the AD-CHP plant owned by the cooperative in terms of circularity and environmental sustainability. Such choice is due to the role of the plant activities in the overall circularity of the cooperative since it allows the production of renewable energy, recycling of nutrients, and waste valorization. An AD-CHP plant can be defined as a system incorporating any of the following: organic waste treatment, renewable energy conversion (production of biomethane) and nutrient recirculation (production of biofertilizers). In this context, circularity indicators are used to assess the degree of circularity of the company's best practices related to the AD-CHP plant operations. To select the most appropriate indicators, previous literature on micro-level circularity assessment for the AFS and Key Performance Indicators (KPIs) designed for the specific needs of the system were explored. Among the studies considered for the selection of the literature base indicators:

- Mancini and Raggi (2021), which identify circularity indicators available in the literature for AD processes.
- Poponi et al (2022), who collect the circularity indicators present in literature for AFS, dividing them by the sustainability areas and the levels of analysis considered.
- Kounani et al., (2023) who identified performance indicators available in literature for the agri-food context and able to assess circularity in olive oil mills.
- Feiz et al., (2020), identified some KPIs for the comparison of different biogas production systems that valorize energy, cost, nutrient, and climate impact.

According to the preliminary aim of the study and the system under analysis, the following indicators for assessing energy balance, nutrient recycling potential and the efficiency of organic waste degradation (Feiz et al., 2020) were selected and recalibrated by the authors and presented in table 2.

Table 2 Overview of the circular indicators selected

Indicator	Formula	Unit	Description	Reference
Biogas efficiency	$I_{b,t} = Q_b / m_t$ Q_b: amount of biogas from the AD of organic waste per day; m_t: total amount of waste generated in that day	Nm3 CH_4 (delivered)/t (food waste at source	Energetic revalorization of organic waste	Mancini and Raggi (2021)/ Feiz et al., (2020)
Energy balance	Primary energy used/MJ CH_4(delivered)	MJ/MJ CH_4	Energy delivered as biogas on primary energy used in the process	Feiz et al., (2020)
Nitrogen recycling potential	kg N (delivered)/kg N (food waste at source)	Kg N/ kg N		Feiz et al., (2020)
Energy self-sufficiency	$ESS_{EE} = \frac{EE_P}{EE_r}$		Capability of the system to cover the energy needs necessary for its operation	Poponi et al (2022)/ Kounani et al., 2023

1.3.4 LCA Modelling

This preliminary study aims to define the environmental impact associated with the production and use of biogas as the center of circular and symbiotic exchanges in the system of the case study. This LCA analysis was conducted following the ISO 14040 and 14044 methodological guidelines (ISO, 2020a, 2020b). The goal of the study is to assess the potential environmental impacts of the AD-CHP processes and the potential environmental benefit due to avoided impacts.

The plant is in Calabria, (Italy) and is fed by cattle sewage and manure, olive pomace, citrus paste, chicken manure, molasses, corn and wheat silage and cheese whey. The FU selected is 1 MWh of electricity produced. The system boundaries cover a "gate to gate" and include: i) the Anaerobic digestion process; ii) the Digestate management and, iii) the power and heat cogenerated in the CHP unit. The AD-CHP plant is located inside the company site. No environmental impacts are contemplated for animal manure and sewage since they are considered wastes of the livestock supply chain. The electricity generated by the CHP plant is then exported to the grid, while the electricity consumed by the AD plant is imported from the grid; this also ensures the plant's operability in case of CHP maintenance or malfunctioning. In addition, the infrastructure of the plants was excluded from the study, since it has proven to have a minor contribution to total environmental impact (Stanchev et al., 2020).

The AD-CHP plant is analysed, accounting both primary and secondary data. It considers the inputs for resource and energy consumption and outputs for emissions, wastes, products, and co-products. Table 3 reports the detailed inventory data per FU. In detail, primary data concerning inputs (feedstock, electricity, heat) and outputs (biogas, digestate, heat and electricity) were supplied by the AD plant employees and referred to the year of production, 2022. The background and missing data are based on scientific literature and databases, namely secondary data on plant production and the electricity generated from the Italian grid extracted from Ecoinvent (Wernet et al., 2016).

Additional outputs with quantifiable benefits (heat and digestate) are produced during the process. To avoid allocation, as indicated by ISO standards, the present study adopts the system expansion method, which allows to consider in the analysis the additional functions related to heat and digestate production. The AD process provides both biogas and digestate. However, the main product is biogas, while the digestate is used as organic fertilizer, which is used as an organic fertiliser both by the company in the agricultural chain and by the cooperative members who supply the inputs to feed the process, contributing to a reduction of mineral fertilizer (urea). The inclusion of avoided products implies the application of the digestate, quantifying the related emissions, instead of conventional fertilizers. In this case, the environmental impacts of the avoided use of conventional fertilizer are subtracted and considered credits. In particular, mineral fertilizer was assumed to be the avoided product for digestate since it is used as organic fertilizer-the reference substance is the content of urea. The heat produced in the cogeneration plant for 981.75 MWh is sent back to the AD-CHP for the heating needs, while the remaining portion is delivered to the farm's dairy. This use of heat makes it possible to avoid production by conventional sources, such as the use of natural gas by means of boilers, which is assumed as a reference scenario given the natural gas supply network reaches the site where the plant is located. Thus, the environmental burden of the avoided heat production can be assumed as credits and be subtracted. The eco-profile of natural gas is extracted by Ecoinvent (Wernet et al., 2016).

The LCA of the systems under consideration was assessed through SimaPro 8 software (PreConsultant, 2010) and is focused on the impact categories selected and the related characterization factors. The environmental impacts of the plant are estimated by using the CML IA baseline V3.07 (CML - Department of Industrial Ecology, 2016) method, selecting the following impact categories: abiotic depletion, abiotic depletion (fossil fuels,ODP, (HT, Fresh water aquatic ecotox., Marine aquatic ecotoxicity, Terrestrial ecotoxicity, AP, EP, and POFP); the IPCC 2021 GWP100 method (IPPC, 2021) is used for calculating the GWP (GWP100); finally, the energy consumption is measured by applying the Cumulative Energy Demand (CED) method. The CED assess the total primary energy requirement, originated from the entire global life cycle (Frischknecht et al., 2007), and included as an additional impact category.

Table 0 Detailed inventory data for AD and CHP operation (per FU).

AD-CHP Plant	Unit	Amount	Data source
Input			
Bovine manure	t	0.376470588	Primary data
Bovine slurry	t	0.235294118	Primary data
Poultry manure	t	0.314469412	Primary data
Whey	t	0.835294118	Primary data
Silage waste	t	0.129411765	Primary data
Olive pomace	t	2.889441176	Primary data
Citrus pulp	t	1.683303529	Primary data
Molasses	t	0.028865882	Primary data
Electricity	kWh	2.941176471	Primary data
Heat (from CHP)	kWh	115.5	Mistretta et al., 2022
Output			
Biogas	Nm3	519.3971804	Primary data
Electricity	kWh	1000	Primary data
Heat	kWh	276.375	Mistretta et al., 2022
Solid digestate	t	0.326941176	Primary data
Liquid digestate	t	3.759294118	Primary data
CO_2, biogenic	t	1.151942471	FIPER, 2018
NOx	t	0.000233729	FIPER, 2018
CH_4, biogenic	t	0.013982172	FIPER, 2018
Heat waste	kWh	20.625	Primary data
Avoided products			
Heat	kWh	15.84155765	Calculated data
Mineral fertiliser	t	0.276375	Calculated data

1.3.5 Results Circularity indicators

1.3.5.1 Biogas efficiency (KPI1)

Biomethane is the main products of biogas production systems, so methane yield is a crucial aspect to assess. For this reason, the circular Biogas efficiency indicator for biogas or Effective methane Yield was applied (KPI_1) (Mancini and Raggi, 2021; Feiz et al., (2020)). The indicator aims to assess the energy valorisation of biodegradable waste and is given by the ratio between the amount of biogas obtained from the AD and the amount of organic waste generated at the analysed system. In this case, we considered the whole biogas production system (namely, the total amount of delivered biomethane produced from food waste at source). The data available from the case study allowed us to simplify the calculation of the indicator, as we only had organic waste (Salguero-Puerta et al., 2019). As reported in table 4, I_{bce} is 43.99 m^3 CH_4 /tonnes of waste. The indicator suggests that for every tonne of organic waste, there is a methane production of 43.99 m^3 CH_4 /ton. This gives an indication not only of valorisation for energy purposes but also to assess the efficiency of waste management mechanisms for reuse and recycling. Higher values imply better process performance.

Table 4 KPI1 calculations.

Input	Value	Unit
Biogas produced	4,414,876.03	m^3
Methane % in biogas	55	%
Methane produced	2,428,182	CH_4
Waste collected	55,186.68	ton
I_{bce}	43.99	m^3 CH_4 /ton

1.3.5.2 Energy balance (KPI2)

To assess the energy performance of biogas production from food waste, the ratio of the amount of electricity produced and delivered in terms of biomethane to the amount of primary energy used to produce and distribute this energy is evaluated. The CED (Cumulative Energy Demand V1.11 / Cumulative energy demand) is calculated using the SimaPro software. Incoming electricity on heat and delivered electricity. The value is then reported in MJ. The value is 0.005 MJ/MJ. If the indicator is less than 1, the system is self-sustaining, although it takes electricity from the grid. The details of the calculation are presented in table 5.

Table 5 KPI2 calculations.

Input	Value	Unit
Electricity delivered	1,800	MWh
Electricity used	23.14	MJ
Heat delivered	2,349.18	MWh

1.3.5.3 Self-sustaining capacity (KPI3)

Next, the self-sustaining capacity of the AD-CHP plant was evaluated, adapting the self-sufficiency indicator proposed in literature (Poponi et al., 2022; Kounani et al., 2023). To do this, the ratio between the energy produced and re-utilised by the plant and the total energy required by the plant for its operation, i.e. internally produced thermal energy and electricity from the electricity grid and thus subject to the national energy mix, was assessed. As a result, the AD-CHP plant manages to cover 97.5% of its own thermal energy needs through self-produced energy.

1.3.5.4 Nitrogen recycling potential (KPI4)

One of the sub-products of the AD-CHP plant is digestate which contains relevant macronutrients required for plant growth such as nitrogen (N), phosphorus (P) and potassium (K). The use of digestate instead of mineral fertilizer in crops allows to recycle (reuse or recirculate) such nutrients (Feiz et al., 2020). Thus, the present analysis adapts and adopts the Nitrogen recycling potential (Møller et al., 2023; Feiz et al., 2020). This indicator is given by the ratio between the nitrogen content in the digestate and the nitrogen content of the process inputs, i.e. the various categories of organic waste considered. The nitrogen content of the digestate was extrapolated from primary data, while the potential content of the input through average literature data, shown in the table below (Table 6). The indicator gives us information on the percentage of nitrogen recycled through the digestion process, so the higher the value, the greater the system's ability to recycle this macronutrient. In our case, 21% of the nitrogen produced is 'recycled'.

Table 6 KPI4 N content per waste stream

Input	Value	Unit	N %	Reference
Cattle manure	3,200	ton	2.66	Shah et al., 2014
Sewage sludge	2,000	ton	4.7	Leone et al., 2021
Whey	7,100	ton	0.14	Wasserman, 1960
Wheat	1,100	ton	0.4	Paritosh et al., 2017
Olive mill pomace	12,578	ton	0.87	Leone et al., 2021
Agrumes pulp (fruit waste)	11,317	ton	1.36	Shah et al., 2014
Chicken manure	2,570	ton	1.95	Hachicha et al., 2009
Melasso (fruit waste)	210	ton	1.36	Paritosh et al., 2017

1.3.6 LCA Results

The LCA results are reported in Table 7, where all the impacts are expressed per FU. Considering the AD-CHP activity, the only environmental impacts reported refer to GWP, HT, AP, PO and finally EP. GWP is the most relevant hotspot for the AD-CHP plant. The main emissions are related to the macro pollutants methane biogen and nitrogen oxides. The former affects GWP and PO, while the latter affects HT, AP and EP, according to the quantities mentioned above. Overall, the most relevant macro pollutant at this stage is methane biogen, whose high presence is partly related to the portion of biogas not captured. This portion reduces the production yield as these uncaptured methane emissions have a direct impact on GHG emissions from plant operations. Considering the electricity consumed, the highest impacts are recorded in terms of MAE, Abiotic Depletion-fossil fuels , and CED. The former is mostly due to emissions of hydrogen fluoride in the air (333 kg 1.4-DB eq) and Beryllium in water (187 kg 1.4-DB eq). The second, on the other hand, is mainly due to emissions of natural gas (9.08 MJ) and coal (3.01 MJ). Finally, the high CED value is more related to non-renewable, fossils.

In general, the worst environmental performance in the most impact indicators derives from the use of energy from the grid to power the process, this is due to electricity from the national grid which is essentially attributable to the relevant contribution of fossil fuels in the Italian electricity mix.

The model also considers avoided production, i.e. it includes the environmental credits associated with the avoided production of mineral fertiliser and gas from fossil sources. Including such products is a common LCA practice where the activity analysed involves the avoided production of conventional products or primary materials (Salomone et al., 2018). Considering the environmental credits, the avoided urea due to digestate utilisation as fertiliser has a relevant positive impact. Specifically, the largest absolute credits are in terms of MAE, AD, and CED. Regarding the avoided use of natural gas from heat delivered by the AD-CHP plant, significant is the saving of MAE, 81.24 kg 1.4-DB eq, and CED, -76.48 MJ. Thus, the environmental credits significantly reduce the amount of MAE and CED. Analysing the two impact categories in more detail shows how the benefit from both avoided fertiliser and avoided natural gas is more related to savings in terms of non-renewable, fossil impact. In conclusion, the results suggest that using the AD-CHP plant is environmentally efficient, given the significant benefits due to the environmental credits associated with the avoided use of mineral fertilisers and fossil natural gas, replaced by the digestate and heat produced by the plant. In short, the profile of the analysed AD-CHP plant, including avoided productions, showed the reduction of environmental impacts compared to a linear scenario. The solution chosen by Fattoria della Piana regarding the AD-CHP plant is environmentally valid regarding the AD-CHP plant is environmentally valid.

Table 7 Environmental impacts and credits displayed per FU – Characterization results.

Impact category	Unit	Impacts		Credits	
		AD-CHP	Electricity	Mineral fertiliser (avoided product)	Heat from natural gas (avoided product)
Ozone layer depletion	**kg CFC-11 eq**	**0.00**	**0.00**	**0.00**	**0.00**
Abiotic depletion	**kg Sb eq**	**0.00**	**0.00**	**0.00**	**0.00**
Photochemical oxidation	**kg C2H4 eq**	**0.08**	**0.00**	**-0.04**	**0.00**
Terrestrial ecotoxicity	**kg 1.4-DB eq**	**0.00**	**0.00**	**-0.13**	**0.00**
Eutrophication	**kg PO4--- eq**	**0.03**	**0.00**	**-0.21**	**0.00**
Acidification	**kg SO2 eq**	**0.12**	**0.00**	**-1.05**	**0.00**
Fresh water aquatic ecotox.	**kg 1.4-DB eq**	**0.00**	**0.13**	**-26.35**	**-0.02**
Human toxicity	**kg 1.4-DB eq**	**0.28**	**0.14**	**-34.98**	**-0.07**
Abiotic depletion (fossil fuels)	**MJ**	**0.00**	**13.68**	**-8,164.16**	**-68.46**
Marine aquatic ecotoxicity	**kg 1.4-DB eq**	**0.00**	**629.84**	**-72,959.86**	**-81.25**
GWP100	**kg CO2-eq**	**380.32**	**1.04**	**-326.14**	**-3.96**
Cumulative Energy Demand	**MJ**	**0.00**	**23.14**	**-9,343.26**	**-76.48**

1.3.7 Circularity indicators and LCA: A combined approach

The LCA study shows the environmental benefit associated with the AD-CHP plant due to the benefits of not using mineral fertiliser and heat from natural gas, as represented in figure 2. In circularity, however, it is not easy to settle on a single level in the evaluation. Analysing individual aspects, as far as energy is concerned, only GWP and PO impacts due to methane Biogen are associated with the plant. The presence of KPI_1, summarised in table 8, allows to integrate this information with an evaluation of the energetic valorisation of biodegradable waste, i.e. the ability to recover energy from food waste, equal to 43.99 m^3 CH_4 /tonnes of waste.

KPI_2, on the other hand, evaluates the energy balance, i.e. the plant's ability to self-support itself in terms of energy, as the energy produced from biomethane is sufficient to cover the plant's primary energy needs. KPI_3 then allows us to assess the plant's self-supporting capacity, this time applied to heat only. In this case, too, there is almost total coverage of heat requirements (97.5%). Thus, from an environmental and circularity point of view, the AD-CHP system is environmentally sustainable due to its good ability to cover its energy needs and thus recover energy through waste.

Considering the fertiliser, the LCA emphasized environmental credit, especially in terms of MAE, AD, and CED. In digestate, there is indeed greater plant availability of nitrogen, especially ammonium nitrogen (Feiz et al., 2020), than N in untreated waste. Thus, its use instead of mineral fertilizer impacts the overall demand for additional nitrogen, reducing the emissions associated with the production and spreading of mineral fertiliser (Moller et al., 2023). In this context, KPI_4 assesses that 21% of nitrogen incorporated in the digestate is recycled. Thus, the environmental credit found is associated with an effective recycling of the nutrients produced. Thus, in this case, the combined approach yielded consistent outcomes, defining the strategies adopted by the cooperative about the AD-CHP plant as circuitous and environmentally sustainable.

Figure 2 Impact assessment per FU

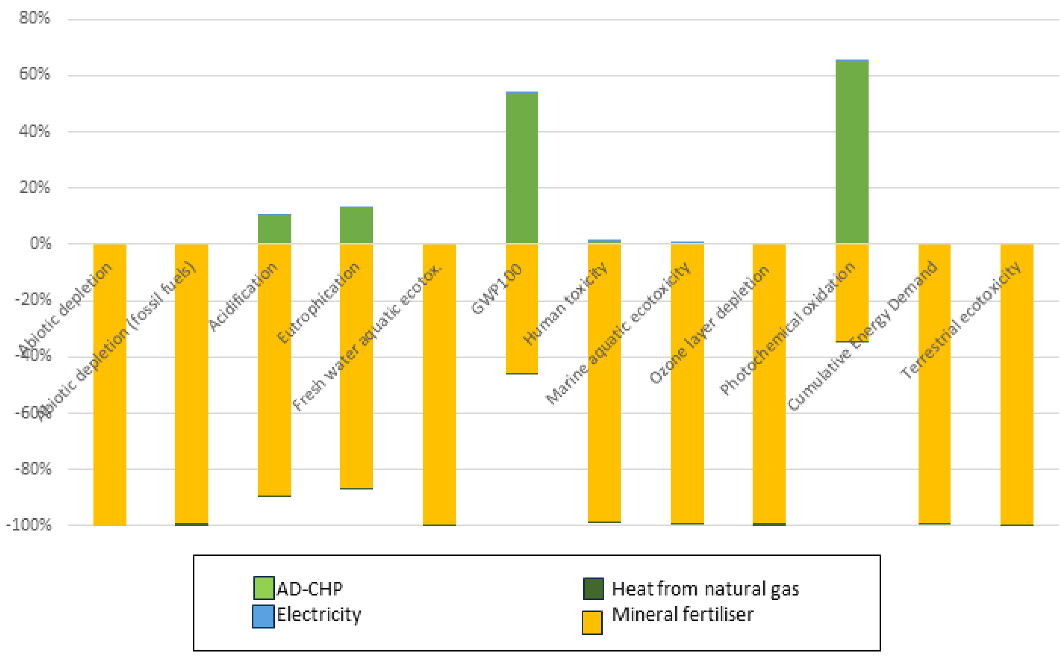

Table 8 Overview table of the KPIs adopted.

KPI_1	KPI_2	KPI_3	KPI_4
Biogas efficiency[a]	Energy balance[b]	Self-sustaining capacity[c]	Nitrogen recycling potential[d]
m^3 CH_4 /tonnes of waste	MJ/MJ	MWh	Kg
43.99	0.005	97.5%	21%

[a] Higher values imply better performance.
[b] Lower values imply better performance; expected to be < 1.
[c] Higher values imply better performance.
[d] Higher values imply better performance (closer to 1.)

1.4 Discussion

The LCA analysis showed a significant environmental benefit from the AD-CHP plant. In addition, the environmental credit associated with the production of energy and digester through the plant is higher than that from the production of compost alone. Thus, while the environmental benefit associated with the AD-CHP plant is undeniable, an assessment of its level of circularity is more complex to define. The system could be interpreted as a strategy to close the resource loop through the production of bioenergy and the recycling of nutrients through digestate (Moller et al., 2023). However, it should be highlighted that the scheme provided by the Ellen

McArthur Foundation, the so-called “butterfly diagram”, consider anaerobic digestion the penultimate strategy in terms of circularity before the extraction of biochemicals as feedstock. This is because the CE aims to keep the resources at the highest value for as long as possible (Korhonen et al., 2018), so energy recovery, which does not involve subsequent uses of the materials, is considered limitedly circular. The same considerations apply to the R framework, which is widely used to identify circularity strategies in the literature (Luthin et al., 2023). Considering the 9R scheme defined by Potting et al. (2017), energy recovery lies between R8 (Recycling) and R9 (Recover), last on the priority scale.

This suggests, as already highlighted in the literature (Rigamonti and Mancini, 2021), that a circular strategy is not necessarily more environmentally sustainable. Hence, an urgency to measure circularity to ensure that implemented strategies adhere to CE principles while being environmentally, economically, and socially sustainable (Falcone et al., 2022). From a methodological point of view, LCA and circularity indicators provide different but complementary information. The LCA assesses the potential environmental impacts associated with the entire life cycle of a product, identifying possible hotspots. Circularity indicators, on the other hand, allow us to assess whether and to what extent certain circular strategies can increase the circularity of a system (Samani, 2023). LCA does not propose strategies but can support decision-making for circularity implementation (Pena et al., 2021). Overall, competing but complementary approaches must be evaluated and integrated to ensure a real absence of rebound effects (Leipold et al., 2023).

Another critical element is the evaluation of the boundaries of the analysed system. Considering the system of symbiotic exchanges that allow the company to find the waste used as input for the plant, one can speak of strategies to reduce or reuse the quantity of waste produced, thus increasing the level of circularity of the system. Therefore, the circularity and environmental sustainability of a system is strongly influenced by the instruments and the perspective of analysis, which require case-by-case evaluations.

Although there is not yet detailed data on the entire system, we can nevertheless affirm the environmental and economic benefit obtained by the cooperative and its partners in channelling their waste and scrap to the AD-CHP plant. When considering the entire system, beyond the recovery of energy, there is an effective reduction in the amount of waste, as well as its total reuse. The evaluation of avoided products further supports the hypothesis of environmental sustainability, given the considerable loads avoided due to the lack of production of mineral fertiliser, which in the case of the cooperative is replaced by digestate, but is also supplied to partner companies who, through a reverse logistic mechanism, bring back the digestate obtained in a single trip. Furthermore, the waste and input exchange mechanism are not linked to a compensation logic, so the cooperative has created a spontaneous exchange system with a significant social impact. The system unites partners in the area with different activities, but all are united by the need to properly dispose of their organic waste.

The application of CE principles has therefore allowed the company to reduce and reuse the organic waste produced, reducing the related disposal costs, generating thermal energy to sustain the dairy's production activities, the creating an additional source of income due to the incentives for the electricity fed into the national grid, as well as the total replacement of mineral fertiliser with internally produced digestate.

1.5 Conclusions

In conclusion, according to this preliminary analysis, the solution chosen by the cooperative regarding the AD-CHP plant is circular and environmentally sustainable. The preliminary assessment has made it possible to identify the main environmental impacts associated with the AD-CHP plant owned by the Fattoria della Piana cooperative, as well as to measure its relative circularity. The analysis generated a reflection on how circularity and sustainability do not always go hand in hand and how it is necessary to carry out case-by-case evaluations to establish the efficiency of the practices implemented. The preliminary analysis conducted confirmed the circularity and sustainability of the strategies adopted by the cooperative concerning the AD-CHP plant. Although, this is a preliminary study, the final objective of which is to map all the chains characterising the cooperative, the context analysed provides insights into crucial factors that could guide practitioners of the food sector to build circular systems. It should also be remembered that circularity does not only embrace environmental sustainability but also economic and social sustainability. For this reason, future developments of this study also envisage an assessment of these two spheres based on LCC and S-LCA methodologies, combined with appropriate indicators. The conducted analysis cannot but generate a reflection on the possibility of adequately measuring and monitoring the strategies implemented with a view to circularity in a sector as central to the sustainable transition as the agro-food sector. At present, the lack of an unambiguous approach to circularity performance measurement is one of the obstacles to CE adoption in the sector, since it makes it difficult for companies to include circularity in their business strategy (Kumar et al., 2022). Therefore, in order to foster a greater application of circularity in the sector, it is necessary to guide companies towards mechanisms for measuring and communicating the performance resulting from the application of CE, considering the peculiarities of the sector and assessing not only the environmental but also the economic and social impact of the strategies implemented. To this end, the following chapter will focus on the design and validation of a framework capable of guiding and facilitating the measurement of circularity through a combined approach of life cycle thinking (understood also in its economic (LCC) and social (S-LCA) components) and the selection of circularity indicators capable of exploiting the high number of organic flows characterizing the sector.

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Chapter 5: Insights for a framework to assess and report circularity in agrifood sector

1.1 Introduction

The AFS has faced relevant transformations since the 1950s which have severely impacted the overall society. The intensification of the production activity allowed it to meet the rising food demand but also increased the consumption of energy and agrochemicals. Such a production model generated positive and negative externalities. Some developing countries have become major producers of high-value-added products such as palm oil; this led to more services and jobs on the territory but also generated an over-exploitation of natural resources, with repercussions for the whole society (Castillo-Díaz et al., 2023). These issues make it necessary to steer the sector towards a sustainable model, i.e. one that can limit the negative externalities associated with the current model of food production and consumption, promoting strategies that can preserve the ecosystem and generate development at an economic and social level. The centrality of the AFS in the transition to sustainable development has been evidenced in academic studies (De Bernardi et al., 2023; Poponi et al., 2022; Silvestri et al., 2022) but also at the policy level. In 2015 the United Nations defined the 2030 Agenda which identified the main areas of intervention to ensure a transition towards sustainable development and is articulated in 17 SDGs. Along this line, the 'Farm to Fork' strategy, included in the European Green Deal (European Commission, 2019), highlighted the need to promote a responsible and sustainable food production model for the overall society and circular business models, capable of generating new business opportunities e.g. related to the reuse of food waste (European Commission, 2020a). Finally, the CAP guidelines for the period 2023-2027 emphasise the need to maintain continuity with the Farm to Fork strategy, e.g. by contributing to the target of 25% of European farmland being organic, reducing the use and risk of chemical pesticides by 50%, and preserving high diversity landscape features, all by 2030 (European Commission, 2023).

In this context, CE could contribute to a new balance between the environmental and economic systems if directed towards sustainability (Falcone et al., 2022). However, there is growing concern about how to define and implement circularity principles, especially among CE practitioners (Pena et al., 2021). Despite the sector complexity and centrality in the circular transition, the lack of CE assessment is considerable in the AFS (Coluccia et al., 2023). To date, the only reference standards applicable to companies of the AFS, are the BS 8001 (BS, 2017) and XP X30-901 (AFNOR, 2018). The first is a practical guide to the adoption of CE for companies provided by the United Kingdom. The standard identifies six circularity principles (systems thinking, stewardship, transparency, collaboration, innovation, value optimization) to guide companies towards CE and presents a flexible framework useful to define a road map for its implementation at the business level (BS 8001, 2017). However, BS 8001 has a descriptive and not a prescriptive nature, thus it does not contain specific requirements (Roos Lindgreen et al., 2021).

Today several factors limit the implementation of CE at the company level (Falcone et al., 2022). To overcome such factors and foster a circular transition, is crucial to adopt appropriate and effective measurement tools to monitor the strategies implemented (Roos Lindgreen et al., 2022; Ruggieri et al., 2022). The lack of a standardized assessment method for CE has been evidenced as a limit to its development (Roos Lingreen et al., 2021). The same lack is perceived in the AFS, where the complexity of the food supply chain makes it even more challenging to find a common assessment framework (Poponi et al., 2022; Silvestri et al., 2022; Ruggieri et al., 2022). A reference standard for CE measurement is now available for the Italian context: the UNI/TS 11820:2022. The technical standard, published in 2022, is based on a set of 71 indicators and aims to assess the level of circularity at the micro and meso level without being sector specific. The UNI/TS 11820:2022 is a step that is part of a broader path that will lead to the development of the ISO 59000 series which will provide more information on the implementation and evaluation of CE. However, the Technical Committee (TC323) (ISO, 2023) is still working, so there is no common reference for companies in the food and non-food sectors. So far, several assessment metrics have been proposed in the literature; most tackle specific aspects of CE (Corona et al., 2019; Saidani et al., 2019), while a limited fraction address circularity and sustainability at the same time (Falcone et al., 2022). Regarding the latter point, CE could be a driver for sustainability, but the two concepts do not coincide. Such lack of clarity makes it difficult for scholars to propose and practitioners to adopt suitable assessment methods (Mancini and Raggi, 2021). Currently, there is no common point on CE metrics' capacity to foster the environmental performance of companies (Gallo et al., 2023). Thus, no framework guarantees that a specific CE strategy generates improvements environmentally and socially (Ruggieri et al., 2022). The lack of consideration for the social aspect of sustainability seems relevant (Mancini and Raggi, 2021). Indeed, circularity may generate relevant spillover effects if socioeconomic factors are not adequately considered (Pena et al., 2021). Despite the various metrics for measuring circularity (Moraga et al., 2019; Brändström and Saidani, 2022), these instruments alone are incomplete for an effective and holistic assessment of CE.

As evidenced by Leipold et al. (2023), interdisciplinary links are critical to foster a systemic vision of CE; it is not necessary to devise additional methods but to refine what already developed by sustainability scientists and adapt it to the desired context. The main critical issues related to the measurement of circularity have already emerged, so it would be appropriate to build on what is present in the literature, trying to combine existing instruments. Thus, based on the gaps identified in previous chapters, this study aims at developing a CE assessment and reporting framework for agri-food companies. The goal is achieved through a theoretical structure based on existing literature and adapted to the AFS context, allowing to give insights for the development of a preliminary conceptual framework to assess and report sustainability and circular economy Thus, the innovativeness does not lie in proposing new methods or indicators for CE assessment but on using what already exists in literature to propose a new framework aligned to the EU taxonomy and the Social taxonomy proposed by the Platform for Sustainable Finance. The framework was then validated through interviews with four companies implementing CE and operating in the AFS.

1.2 Theoretical overview

1.2.1 Circularity and Sustainability assessment

Despite the complexity and strategic value of the AFS in the circular transition, a general lack of CE assessment characterizes the sector (Coluccia et al., 2023). A recent review investigated the most relevant metrics for assessing CE in the agri-food context, indicating multi-criteria decision analysis, data envelopment analysis and LCA as the most used to assess the restorative capacity and efficiency of agricultural systems (Rodino et al., 2023). To measure and evaluate circular strategies, Pagotto and Halog (2016) proposed a framework based on Input-Output analysis to assess the resource efficiency and competitiveness potential of CE in the Australian agri-food industry. More recently, Agnusdei et al. (2023) designed a methodological framework for the evaluation of circular alternatives based on digital transformation in the agroindustry supply chains.

However, when circularity is investigated in the agri-food chains, it is rarely considered a complex system, not including stakeholders' perspectives (Rico Lugo et al., 2023). To fill this gap, Coluccia et al. (2023) proposed a novel multi-level framework for assessing circularity holistically in agri-food industries, excluding the agricultural phase. The framework provides a theoretical model, a set of indicators with a weighting system based on an analytical hierarchy process, and finally proposes a geometric multi-criteria decision-making model. However, some authors argue that there is no need to develop further measurement tools but rather to combine traditional approaches with circularity indicators. (Ruggieri et al., 2022; Gallo et al., 2023). In this line, Thakker and Bakshi (2021) and Luthin et al. (2023) proposed frameworks based on the life cycle approach of products and processes. Specifically, Thakker and Bakshi (2021) presented a computational framework to explore existing circular strategies by combining LCA with optimisation-based solutions, while Luthin et al. (2023) proposed a circular life-cycle sustainability assessment framework based on the integration of life cycle thinking (expressed as life cycle assessment, life cycle costing and social-life cycle assessment) with circularity assessment metrics, precisely to the MCI.

The life-cycle approach is widely used in the literature for measuring the potential environmental impact of products or services. It is a standardised approach that can provide a holistic assessment of implemented circular strategies, evaluating environmental, social and economic implications (Pena et al., 2021). To date, it is one of the most widely used methods for measuring circularity (Rigamonti and Mancini, 2021). It is, therefore, It is, therefore, a central tool to measure circularity that embraces sustainability at multiple levels, whereas the currently available indicators seem only able to analyze single aspects of circularity. (Saidani et al., 2019).

The AFS poses relevant challenges to CE assessment due to the complexity of the agri-food supply chain, such as the high product differentiation but also for its intrinsic characteristics such as perishability (Rico Lugo et al., 2023). Moreover, applying circularity in the AFS often requires adapting to local conditions e.g., in case of strategies to improve the nutrient circularity of a company (Fleitas Girett et al., 2023). Thus, the AFS needs specific attention for its centrality in the transition to sustainability but also for its unique characteristics. Hence, the need to support companies of the AFS in implementing and measuring circularity in continuity with sustainability is expressed in an environmental, economic, and social perspective.

1.2.2 Circularity and sustainability reporting

At the company level, assessing the impact of circularity generates relevant internal and external benefits. Internally, companies can identify hotspots in their production lines and optimise the existing strategies while externally communicating and reporting their performance to stakeholders (Roos Lingreen et al., 2022).

The value of CE assessment and reporting is considered at the European policy level. A relevant example is Regulation (EU) 2020/852, the so-called EU Taxonomy (European Commission, 2020b). It introduced six environmental objectives, with number 4 focusing on the transition to a circular economy aimed at classifying economic activities that positively contribute to one of the goals, respecting minimum social standards while not affecting the others, according to the Do No Significant Harm (DNSH) principle (Becchetti et al., 2022). Another example is the SFDR (European Commission, 2022a) which requires the disclosure of information regarding the environmental sustainability of an investment, mentioning CE as an environmental target (Article 2 (17)). Finally, the new CSRD increases the quantity and quality of data to disclose, extending reporting obligations to listed Small and Medium Enterprises (European Commission, 2022b). This indirectly affects suppliers and subcontractors who must deal with the new requirements posed by reporting companies (Becchetti et al., 2022). Companies subject to the CSRD will have to report according to ESRS, which encompass Resource Use and Circular Economy (ESRS 5). It guides companies in assessing impacts, risks and opportunity management, as well as identifying metrics, and targets. Thus, companies will include CE in sustainability reporting in the very next future (European Commission, 2023).

Moreover, the rising importance of CE in the international debate, pushes investors, regulators, and other financial stakeholders to develop screening and eligibility criteria to understand how companies contribute to CE and sustainability. In this context, the example provided by the framework designed by S&P Global Sustainable1 (S&P Global, 2023) is based on Article 2(17) of the SFDR to identify and value sustainable investments. The "S&P Global SFDR Sustainable Investment Framework" consists of good governance screening, e.g., based on the lack of controversies related to employee relations or tax compliance. The DNSH screening, articulated in environmental objectives derived from the EU Taxonomy and social ones derived from the *Social taxonomy*, defined by the Platform for Sustainable Finance in their Final Report on Social Taxonomy. Finally, the positive contribution assessment, where companies prove the presence of sustainable best practices throughout their value chain (S&P Global, 2023). Another relevant example of sustainability assessment is the GIFT, developed by the Italian Ministry of Environment, Land, and Sea Protection. The tool, focused on the environmental dimension of sustainable finance, aims to provide metrics for assessing the environmental performance of public and private investments, adopting a life cycle thinking perspective. GIFT integrates LCA-based performance indicators within sustainable finance, enabling a broader consideration of the environmental mechanisms and fostering consistency with the EU Taxonomy (Becchetti et al., 2022).

Thus, companies urgently need to adequately describe how the Circular Economy (CE) activities implemented are configured within their business models and communicated in their corporate sustainability reports (Opferkuch et al., 2023) to align with upcoming regulations and be ready to attract additional private or public funding. However, sustainability reporting has been limited for companies in the AFS so far. The lack of consistent and coherent reporting information limits potential funders or investors from capturing the potential value of circular projects and strategies implemented by companies (Falkenberg et al., 2023). For this reason, the present framework aims to guide companies to circularity and sustainability assessment and communication.

1.3 Methods: Conceptual Framework development

The framework aims to guide companies of the AFS to the holistic assessment and reporting of the performances of their circular strategies. The conceptualization of the framework consisted of two stages. First, a critical analysis and synthesis of the outcomes that emerged in the literature review (Chapter 2), the empirical analysis (Chapter 3), and the case study analysis (Chapter 4) allowed us to identify the core objectives of the framework.

The critical framework characteristics are:

i) modularity, as it provides flexibility e.g., in the selection of desired assessment configuration depending on their aim and scope of assessment;
ii) multi-dimensionality, as it proposes a holistic assessment of CE;
iii) adaptability, as it adaptable to company characteristics;
iv) based on existing assessment tools.

After identifying critical characteristics of the framework, a descriptive literature review of previous methodologies for CE assessment and report at the company level is performed to collect studies that align with the previously formulated objectives. A descriptive literature review looks for interpretable patterns in previous literature of a given research area concerning pre-existing propositions or methodologies to generalize research outcomes (Paré et al., 2015). Specifically, existing frameworks are reviewed based on whether they address at least one of the objectives previously formulated. To improve the robustness of the analysis, two standards and guidelines for the adoption of Circular Economy (BS8001, 2017; AFNOR, 2018) and four contributions (S&P Global, 2023; Becchetti et al., 2022; Opferkuch et al., 2023; Arana-Landin et al., 2023) were considered, as they fit the aim of the paper. Finally, the collected methodological material is extracted, adjusted for AFS's context and incorporated into the framework. The overall procedure and the objective identified are presented in Figure 1.

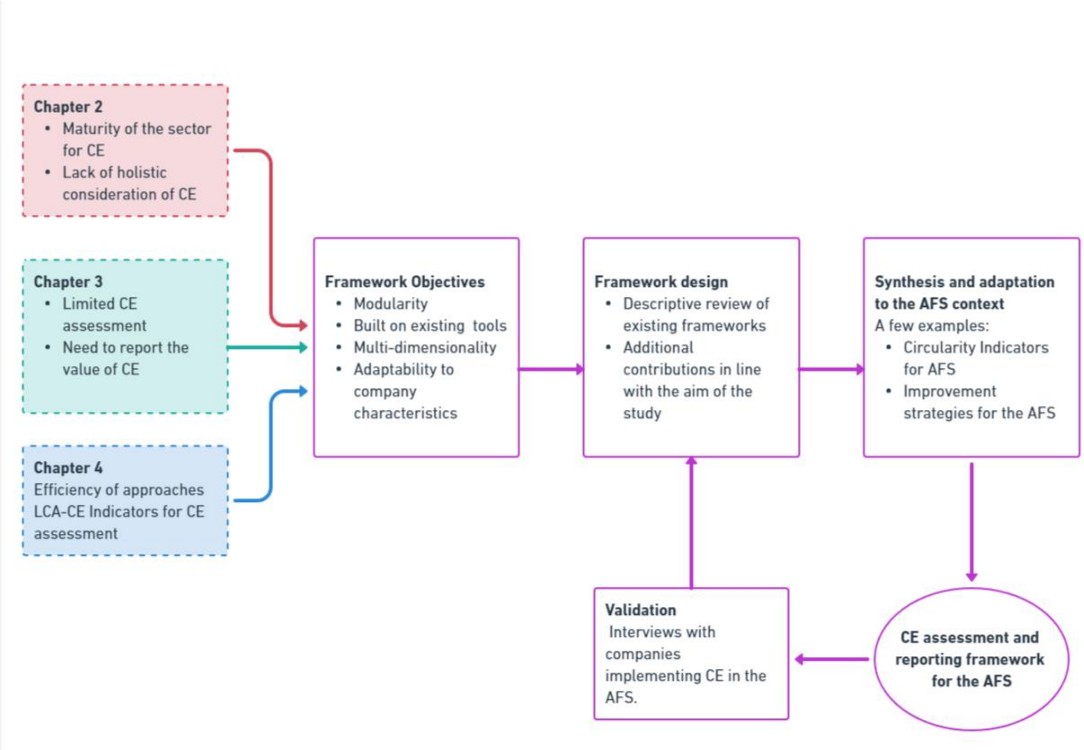

Figure 1: Overview of the methodological approach adopted for the conceptual framework development

1.3.1 Framework validation

The validation process is based on face validity, namely testing the understanding, relevance and clarity of specific items by an intended audience of non-researchers. It can consist of qualitative or quantitative approaches, in the former it usually involves one to one interview or focus groups (Allen et al., 2023).

In this case, the validation process consisted of interviews with industry practitioners to obtain feedback on the framework's clarity, usefulness, and feasibility. The framework is designed on the findings on the previous research steps of the present thesis and thus inspired by the experiences and criticalities faced by the companies involved along the process. For this reason, companies were selected among i) companies with whom a previous deep collaboration had been established (namely, interviewed during the empirical study reported in Chapter 3 and object of the case study analysis reported in Chapter 4) and implementing CE strategies within their business and ii) companies interested in measuring the circularity of their current -or planned- CE strategies (see figure 2)). For this purpose, four companies were selected (see Table 1).

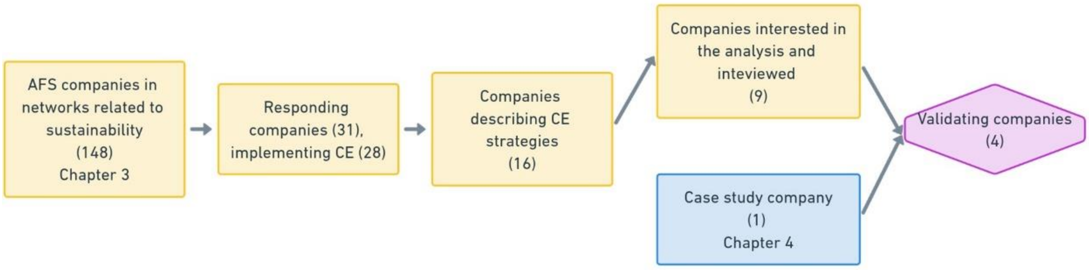

Figure 2 Identification process of the validation sample.

The companies were allowed to provide feedback for each phase of the framework and on the framework. This approach was adopted as a tool to combine scientific research with the perspective of companies potentially interested in the application of the framework. Specifically, three companies were selected during the empirical investigation described in Chapter 2 in the Portuguese agri-food contest and one from the collaboration resulting from the internship activity described in Chapter 3. The selected companies vary in size, which provided the opportunity to include different perspectives (e.g. in terms of operational needs) within the framework. The large Portuguese one is active in the beverage sector, specifically in the production of juices and fruit extracts, and is already measuring circularity through different instruments such as Sustainability reporting frameworks, (Global Reporting Initiative) and various indicators. The medium Italian one, is a cooperative whose main activity is the production of cheese and is not assessing circularity yet. Of the remaining small ones, one is focused on cheese production, while the other on olive oil production and neither of them assess circularity at the moment.

Table 1: Companies interviewed.

Country	Size	Supply chain
Portugal	Large	Beverages
Portugal	Small	Dairy
Portugal	Small	Agriculture
Italy	Medium	Dairy

The sample of companies had a low to medium knowledge mix regarding the measurement of circularity. The sessions were structured as follows: (1) 5 mins to present the gaps encountered and the motivations, (2) 3 mins to illustrate the objectives of the framework, (3) 25 mins providing details on application steps combined with practical examples, (4) 2 mins for conclusion. The sessions took place on the Microsoft Teams platform and were recorded. Feedback was provided on Microsoft Forms via closed and open-ended questions. The questions asked were focused on the clarity of the framework, its usefulness to achieve the illustrated objectives, and its feasibility, but also on its possible adoption, articulating the response.

1.4 Results

1.4.1 Structure and coverage of the framework

This framework has been: i) developed from previous literature examples (Luthin et al., 2023; S&P Global, 2023; Becchetti et al., 2022; Operkuch et al., 2023; Arana-Landin et al., 2023) ii) influenced by standards and guidelines for the adoption of CE (BS8001, 2017; AFNOR, 2018) and iii) designed as a synthesis of these previous experiences, proposing the necessary adjustments for AFS's context. The proposed framework is articulated in three stages listed below and presented in Figure3.

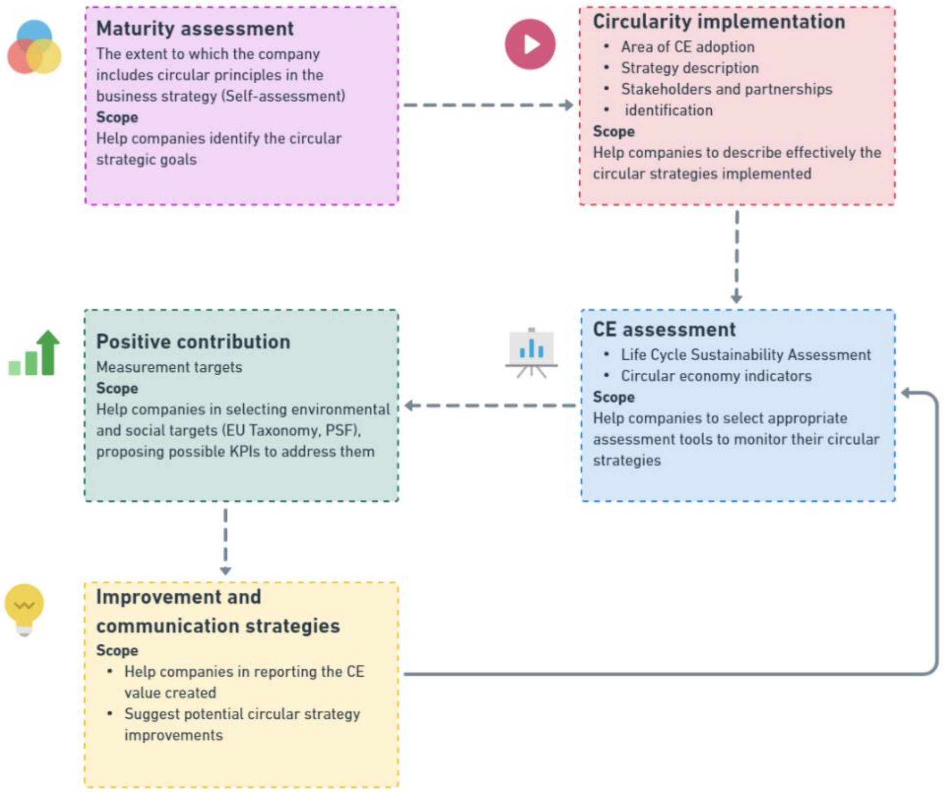

Figure 3: Development steps of the Framework for CE assessment and reporting

1.4.2 Maturity assessment

First, companies need to assess their level of maturity in terms of CE, understood as the level of recognition and inclusion of circularity principles in the corporate vision. This step allows them to understand to which extent they implement circular business models across the different dimensions of the company (Coluccia et al.,2023). The auto-diagnosis helps companies to formalize the strategic vision for CE and to identify possible areas of improvement. This assessment is carried out qualitatively, answering to some questions adapted from BS 8801:2017 and from Niero and Rivera (2018) to contextualize to the AFS. The answers obtained should be analyzed according to a scoring system, adapted from BS 8001:2017, which identifies companies as not engaged (0), limitedly engaged (1), engaged (2), and highly engaged (3).

Questions are based on the six principles identified by BS 8001 as the core principles of the CE:

- “Systems thinking- organizations take a holistic approach to understand how individual decisions and activities interact within the wider systems they are part of”.
- “Innovation- organizations continually innovate to create value by enabling the sustainable management of resources through the design of processes, products/services and business models”.
- “Stewardship- organizations manage the direct and indirect impacts of their decisions and activities within the wider systems they are part of.”
- “Collaboration- organizations collaborate internally and externally through formal and/or informal arrangements to create mutual value”.
- “Value optimization- organizations keep all products, components and materials at their highest value and utility at all times”.
- “Transparency- organizations are open about decisions and activities that affect their ability to transition to a more circular and sustainable mode of operation and are willing to communicate these in a clear, accurate, timely, honest and complete manner”.

Operatively, companies answer the questions in Table 1 and, according to the final score, define their level of maturity regarding CE conceptualization and implementation. Once the self-assessment has been carried out, companies will be able to identify which elements of their strategy need to be improved, as well as to set the next strategic priorities, in line with the circularity principles identified by BS8001.

Table 1 Possible questions to guide companies towards their maturity level of CE, adapted from BS8001 (2017) and from Niero and Rivera (2018) (the list is not exhaustive).

CE principles	Questions
Systems thinking	Does your organization perceive CE as relevant for its long-term resilience? Do you have a strategic plan for your CE activity? Do your circular strategic plans include the whole supply chain? Do they embrace a farm to fork perspective? Have you explored and a set of options to bring the CE to life? Has your organization piloted or experimented with ideas/concepts to test and determine the viability? Has your company successfully integrated ideas and opportunities?
Innovation	Are you investing in technologies to implement new circular practices?? Do you associate circular economy to innovation or to conventional practices? If innovation, as incremental innovation o radical innovation? To what extent is the circular economy a part of your existing business strategy/business model?

	Do you understand how your decisions and activities might be new or transformative or are improvements to existing arrangements?
	Do you apply eco-design principles to your product packaging? E.g., increasing the recyclability of the materials used
	Do you reduce and recover food waste to reprocess it for other applications? E.g., transforming waste oil into biofuels or animal feed
	Do you sustainably source your critical raw materials? E.g., palm oil
	What processes have been put in place to ensure change management is successful?
Stewardship	Does top-level management sufficiently demonstrate commitment to pursue sustainability and circularity logics in its decisions and activities?
	Have current and future economic, environmental, and social risks and opportunities associated with the use of resources across your value chain been determined/assessed
	Will decisions and activities associated with your circular economy objectives change current and future resource risks and opportunities?
	Have steps been taken to mitigate resource risks and opportunities during company's activities?
	Will trainings and informative events be provided to ensure company's alignment to CE and sustainability?
	Are you taking part to campaigns or event to sensibilize consumers to waste relate issues? E.g., campaigns for the reuse of beverage packaging in public events like concerts or festivals
Collaboration	Have you considered collaborations outside of your usual peer group? E.g., food associations
	Have potential collaborative organizations been identified against your circular economy objectives?
	Do you have involved partners in upcycling or ecosystems re-entry mechanisms? E.g., redesigning ingredients or improving the quality of materials to close the loop in terms of resource utilization
	Is the organizational structure suitable and able to provide the flexibility required for collaborative working?
	Do you understand how value is created through collaboration?
	Have you identified issues and areas of improvement?
Value optimization	Have you estimated the economic benefits for the circular economy?
	How are value optimization requirements communicated to the supply chain
	Do you re-use organic waste to produce or recover energy? E.g., through anaerobic digestion
	Do you re-use organic waste to replace fertilisers? E.g., through composting
	Does another party get value from your product at the end of use phase?
Transparency	Do you have certifications or set voluntary commitments for carbon emission and food waste reduction?
	Has resource use been mapped within your value chain, including sourcing and production locations?
	How is information relevant to the sustainable management of resources in products and services made accessible?

Companies have different levels of familiarity with CE: some may already have been implementing circular strategies for some time without being fully aware of it, others may have only recently approached circularity, and others may have already incorporated CE into the company's strategic planning. In any case, companies may present different levels of circularity at the same time. Therefore, an initial assessment of the level of maturity can indicate to the company the areas to improve and identify where and how to focus on their strategic targets. This information will be recalled in the last step of the framework, in which companies will communicate the circular value created in sustainability reporting and disclose their strategic priorities. The scoring system is presented in Table 2, adapted from BS8001, (2017) and shown below.

Table 2: Maturity level of CE: Final score, adapted from BS8001, 2017.

CE principles	**Maturity level**			
	Not engaged (≥1/3 to 1/2 of responses = Partly considered)	**Limitedly engaged** (>1/2 of responses = Partly considered)	**Engaged** (≥1/2 to 2/3 of responses = Fully considered)	**Highly engaged** (>2/3 of responses = Fully considered)
Systems thinking (ST)	Lack of ST	Company's vision for CE is partially developed	ST is central to progress in developing CE strategy and objectives	Company applies ST to CE, investing for the longer-term
Innovation	Limited innovation	Innovation and stakeholder's needs are partially considered in developing CE	CE innovation is stable inside the company and stakeholders	Fostered innovation to generate business value Through sustainable management approach
Stewardship	No real focus on CE	Partial consideration of environmental and social issues in resource management	Key environmental and social issues are part of decisions and activities of relevance to CE	Managing direct and indirect impacts of company's decisions and activities across the value chain
Collaboration	Limited collaboration	Collaborative support is present but partial both across internal stakeholders	Presence of active collaboration examples across businesses	Collaboration is pursued internally and externally to progress company's CE strategy
Value optimization	Limited interest in optimizing resource management	Value optimization importance is recognized across the organization	Active approach to value optimization through resource management engaging also other parties	Materials are kept at their highest value, while residues exchanged with other parties
Transparency	Limited knowledge of resource management issues	Transparency related to the company's circularity journey is recognized but still passive	Visibility of information actively planned across the organization	Open and transparent on information from upstream and downstream partners

1.4.3 CE implementation

Once the level of familiarity with CE has been defined, it is necessary to frame the positioning of the company, i.e. to understand how and where it has implemented CE in its operations. This section is based on the experience gained through the empirical analysis (presented in Chapter 3) and the case study analysis (described in Chapter 4), since companies struggled to contextualize their effort in terms of CE.

1.4.3.1 Areas of action

First, companies must clarify the area of application of the circular strategy. In this sense, the framework proposes seven areas of application: Sustainable supply, Ecodesign, Industrial symbiosis, Functional economy, Responsible consumption, Extension of duration and Effective management of end-of-life materials or products, as summarized by Arana-Landin et al. (2023), in line with the XP X30-901 (AFNOR, 2018). Sustainable supply implies selecting supply chain partners based on environmental and circular criteria, e.g., sourcing inputs from renewable or recovered sources (Dey et al., 2022); Ecodesign, fostering the efficiency of processes and products, e.g., simplifying the end-of-life recovery of products and the efficient use of by-products (Hussain & Malik, 2020); Industrial symbiosis, sharing tangible and intangible resources within a network, e.g., developing a collaborative environment along the supply chain (Dey et al., 2019); Functional economy, developing systems for product recovery; Responsible consumption, meant as the company commitment to circularity, e.g., promoting a responsible use of products, their recycling, and reuse (Fortunati et al., 2020); Extension of duration, prolonging the use of inputs of products, e.g., providing maintenance services; Management of end-of-life materials or products, as adopting strategies less environmentally impactful, e.g., increase the quantity of recycled plastic, reducing the fraction of waste that goes to landfill (Fortunati et al., 2020).

1.4.3.2 CE strategies description and classification

The company then identifies the circular strategies implemented. It describes the CE activities as individual strategies, highlighting main inputs, outputs and processes and then matches the circular strategies according to the 10 R framework -Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover- (Potting et al., 2017). This allows companies to effectively clarify the strategies implemented and provide a possible basis for their integration in sustainability reporting, as suggested by Opferkuch et al. (2023). For example, consider a company in AFS that uses its organic waste as input for energy production via anaerobic digestion. In this case, the company will indicate as input the waste used, e.g. litter, straw, manure, as process the anaerobic digestion, as output energy and digestate and associated to a Recover strategy (R10).

1.4.3.3 Stakeholders' identification

Finally, the company maps the relevant internal and external stakeholders that support its CE strategies. Stakeholders play a relevant role in decision-making processes; in the agri-food context, the multi-objective nature of the sector makes mandatory to combine the objectives and perspectives of multiple stakeholders to avoid segmented empirical decisions (Rico Lugo et al., 2023). First, the company identifies the most relevant stakeholders, and second, it clarifies their interest and involvement with the company in developing its CE strategic plan, evidencing partnerships and collaborations. This step allows the company to assess which actors and collaborations are relevant to the company's circular strategy. Mapping the stakeholders also helps the company to identify new potential partners and collaborations for future developments (BS 8001:2017).

1.4.4 CE Assessment

After companies clarify how they implement circularity, they need to assess the performance of their circular strategies on environmental, economic, and social levels. In this sense, the framework suggests the use of the LCSA, a standardized methodology consisting of LCA, LCC and S-LCA combined with circularity metrics identified in literature specifically for the AFS (Poponi et al., 2022) as explained in the next sub-headings. The indicators allow an effective assessment of the level of circularity of the implemented strategies. Whether the life-cycle approach is considered as a supporting tool that can assess the environmental, social and economic performance associated with the circular strategies, obtaining an overview of the company or an individual product, and identifying the presence of possible hotspots. Proposing an integration of LCA, LCC, and S-LCA is out of the scope of the present framework, given the modularity objective; this allows companies to choose to perform simplified method or calculate selected impact per method (e.g. decent work for S-LCA, etc.), depending on their aim and scope of assessment.

1.4.4.1 Life cycle assessment in the circular economy context

LCA is a standardized methodology structured into four phases: goal and scope, inventory, impact assessment and interpretation. Unfortunately, there is no benchmark to measure the circularity of the strategies implemented in the AFS. To mitigate such issues, companies should check the availability of PEFCRs suitable for measuring the processes and products covered by the circular strategies adopted (European Commission, 2020c). PEFCRs are based on LCA methodology and indicate rules and guidelines for conducting LCA analysis, suggesting methodological choices in line with the characteristics of the products under analysis. Furthermore, they ensure that LCA studies for products with similar functionality are conducted under the same conditions, improving the reliability and comparability of the results (European Commission, 2020c), which is crucial given the current lack of benchmarks. Thus, practitioners have a benchmark by product category, verifying the consistency of the results with the category under analysis.

1.4.4.2 Life cycle costing in the circular economy context

The LCC is considered the economic counterpart to LCA analysis (Falcone et al., 2022). LCC allows estimating the equivalent monetary values of the external costs, e.g., the environmental impacts associated with a product usually not captured by the market logic (Kerdlap and Cornago, 2021). As evidenced by Kanzari et al. (2022), companies investing in circularity need more time before revenues due to multiple life cycles. However, the LCC measures investments and strategies with a long-term perspective, so it is a valuable tool for capturing future financial values in the CE context (Kanzari et al., 2022). Most of the circularity indicators aim to increase the utility of resources, assessing the life cycle value flows associated with a system, which is crucial in CE and sustainability logic (Falcone et al., 2022). Companies should adopt the same methodological choices for the LCA to ensure the consistency of the overall LCSA and enable the comparability of the single analysis.

1.4.4.3 Social life cycle assessment in the circular economy context

The S-LCA methodology helps companies monitor and measure the potential social impacts of the CE strategies implemented. The S-LCA is considered the social counterpart of the LCA and aims to capture all the positive or negative social impacts associated with a product along its whole life cycle. It considers companies part of the supply chain of the analysed product, analysing how the different stakeholders interact and impact at the social level (Walker et al., 2022). As evidenced by Luthin et al. (2023a), analysing the possible tools for evaluating circularity in the social field, an S-LCA conducted according to the UNEP guidelines is a valid tool for capturing the social impacts of circularity.

1.4.4.4 Circular economy indicator selection

Concerning the selection of the CE indicator, several studies in the literature analyzed indicators for CE (Corona et al., 2019; Saidani et al., 2019; Roos Lindgreen et al., 2021). So far, most circularity indicators focus on assessing technical systems based on inert material. However, food systems mainly entail organic material, which is exhausted after use (Møller et al., 2023). Thus, the framework considered only studies presenting circularity indicators targeted for the AFS. Among the relevant contributions, the study of Poponi et al. (2022) was selected as the primary source of circularity indicators for its completeness. The study collected all the available CE indicators present in literature, targeted the AFS and created a dashboard articulated per spatial dimensions (micro, meso, macro) and sustainability pillar (environmental, economic, and social). Given that the framework is focused on company level, only indicators for micro level of assessment were considered. Thus, companies in the sector should select the indicators more suitable for their specific activity among those identified from the dashboard developed by Poponi et al., 2022. The reference dashboard is reported in Appendix (Table A1).

1.4.5 Positive contribution

1.4.5.1 Objectives definition

After identifying the strategies implemented and the relevant stakeholders, companies measure and communicate their performance in terms of circularity. To do so, it is first necessary to identify the principles and objectives to be set. In this sense, Article 2, point (17) of the SFDR (European Parliament and Council, 2022) introduces the principle of DNSH and in providing a definition of sustainable investment, identifies general objectives of an environmental and social nature. Specifically, according to the directive, an investment is sustainable if “*contributes to an environmental objective, as measured, for example, by key resource efficiency indicators on the use of energy, renewable energy, raw materials, water and land, on the production of waste, and greenhouse gas emissions, or on its impact on biodiversity and the circular economy, or an investment in an economic activity that contributes to a social objective, in particular an investment that contributes to tackling inequality or that fosters social cohesion, social integration and labour relations, or an investment in human capital or economically or socially disadvantaged communities, provided that such investments do not significantly harm any of those objectives and that the investee companies follow good governance practices, in particular with respect to sound management structures, employee relations, remuneration of staff and tax compliance”.*

In identifying measurement targets, the framework proposes to follow the environmental objectives indicated by the EU Taxonomy and the social objectives set by the Final Report on Social Taxonomy (PSF, 2022) for companies to assess their performance. To measure to what extent companies' circular strategies, contribute to the identified goals some Key Performance Indicators (KPIs) are presented in the following sub-sections. By KPIs is meant a set of metrics a set of metrics covering the most critical performance aspects of a company for its current and future success (Domínguez et al. 2019). The following paragraphs present the considerations for the two types of objectives.

1.4.5.2 Environmental indicators

Concerning the environmental objectives, the EU Taxonomy defines 6 targets: Climate change mitigation; Climate change adaptation; Sustainable use & and protection of water and marine resources; Transition to a circular economy; Pollution prevention and control; Protection and restoration of biodiversity and ecosystems.

To measure environmental performance, companies should select key performance indicators calculated on previous LCA analysis (ISO 14040; ISO 14044). At this stage of development, the present framework proposes a limited number of indicators to define the level of attribution to the objectives. The main goal was to provide a manageable and immediately implementable approach for the companies in the sector, postponing the possibility of enriching the framework with new indicators. KPIs are calculated by defining a priori the same functional unit; boundaries of the system, in terms of time and life cycle stages; and boundaries of avoided-modified activities that allow for counterfactual assessment.

The approach here proposed was adapted from GIFT, a life-cycle approach designed to assess the environmental performance of financial investments through counterfactual analysis (Becchetti et al., 2022), i.e. on the comparison between the scenario in which the circular strategy took place and the linear one in which it did not. Specifically, the delta interval, given by the difference between the initial and final value of the KPI, is measured. When the difference assuming negative values, the KPI recorded a decrease in the environmental impact associated with the strategy. It is relevant to remember that to be in line with the DNSH principle, the improvement of the performance of a KPI must not compromise the performance of the other indicators.

To this aim, some KPIs already developed in literature are presented to measure the environmental objective of the company, based on the EU Taxonomy (Climate change mitigation; Climate change adaptation; Sustainable use & and protection of water and marine resources; Transition to a circular economy; Pollution prevention and control; Protection and restoration of biodiversity and ecosystems). The KPIs identified allow companies to reduce the complexity associated with the chosen measurement methodologies and transfer information on environmental performance in a clear and timely manner to their stakeholders. The framework proposes a list of existing KPIs suitable for the agri-food sector that companies can select. The list is an initial proposal for measuring the identified objectives and is presented below.

- Climate change mitigation is measured as ‘net emission of GHGs’, expressed in terms of kg CO_2, with a characterization model based on a reference of GWP over 100 years of IPCC (Becchetti et al., 2022).
- Climate change adaptation is measured by the climate change vulnerability proxy. By vulnerability, it meant how much a system can cope with the effects of climate change. Specifically, the indicator considers the type, magnitude,

and rate of such change, as well as the rate of variation that the system is exposed to, its sensitivity and adaptive capacity.

$$Climate\ change\ vulnerability\ proxy = {}^{E \times S}/_{AC}$$

Where E, indicates the exposure of the circular strategy under analysis to extreme climatic events during a given time horizon (Extremely Low: 0.1; Low: 0.2; Medium: 0.5; High: 0.8; Extremely High: 1). The value is based on analysis of past climatic trends. S represents the sensitivity of the strategy to such adverse events, namely how much a system could be affected by these events (Extremely Low: 0.1; Low: 0.2; Medium: 0.5; High: 0.8; Extremely High: 1). Finally, AC captures the adaptive capacity of the strategy under analysis, meant as the capacity to cope with climate change, limiting potential damages (Becchetti et al, 2022).

- Sustainable use and protection of water and marine resources are measured in terms of Water scarcity footprint', expressed as m^3 watereq. With a characterization model based on the Available WAter REmaining (AWARE) method (Becchetti et al., 2022).
- Circular Economy is measured through the selection of appropriate indicators based on the area and level of analysis from the list provided in Table A1
- Pollution prevention and control is measured through a set of indicators (Becchetti et al., 2022):
  - i) Emission of particulate matter, expressed as disease incidence (UNEP (2016a) model-Zampori and Pant, 2019)
  - ii) Photochemical ozone formation', expressed as kg NMVOCeq. (LOTOS-EUROS model)
  - iii) Acidification, expressed as mol H+eq. (Accumulated Exceedance model)
  - iv) Freshwater eutrophication, expressed as kg Peq. (EUTREND model).
- Protection and restoration of biodiversity and ecosystems is given by different factors. The proposed approach is focused solely on deforestation and land uses

for anthropic purposes indicators (Becchetti et al., 2022). Thus, the two KPIs are:

i. "Direct land use for anthropic activities" (m^2a), expressed by the extension of land related to the CE activity occupied for anthropic purposes, without green areas.

ii. "Net deforestation balance" (m^2), expressed by the area directly deforested for the CE activity to take place (positive sign) minus the area reforested (negative sign).

1.4.5.3 Social indicators

For identifying the social objectives, the issue is complex since science has a limited role. In this case, internationally guaranteed standards and principles should be the basis for setting and monitoring social goals (PSF, 2022).

As there is no reference taxonomy but social contribution is an integral part of Article 2 of the SFDR, this study considered the objectives of the social taxonomy devised by the PSF, which defines the main social objectives, ideally complementing the EU Environmental taxonomy. The objectives indicated by the social taxonomy are based on internationally accepted reports and documents; however, some are not prescriptive but aim to encourage public and private actors to guide their activities to sustainable development (e.g., the SDGs). Given the interdependence of such principles, the taxonomy adopts a stakeholder-centric approach, namely it identifies the type of stakeholders that impact the business activities analyzed. The analyzed stakeholders are the company's workers (including those along the value chain), consumers, and local communities affected (PSF, 2022). The objectives are i) Decent work; ii) Adequate living standards and well-being for end-users; iii) Inclusive and sustainable communities and societies (PSF, 2022).

At present, however, there is a lack of indicators to guide companies towards measuring and communicating their social performance. For this reason, companies may link the objectives of social taxonomy to the S-LCA methodology in line with the UNEP S-LCA guidelines (2020), as described in the previous step.

This is motivated by the increased focus on the AFS in the new UNEP guidelines for S-LCA (2021-Impact categories), evidenced by the new impact subcategories 'Small

Business Owners' and 'Small Farms/Small Landowners and Farmers', which refer directly to the world of farmers. Commodity hotspots are associated with the agricultural phase, so it is crucial to pay more attention to this sector (Arcese et al., 2023).

Conducting an S-LCA analysis using workers, local community, value chain actors, consumers, and society as stakeholder categories would bring the objectives of the taxonomy closer to S-LCA logic, providing an assessment of the potential social impacts of a company's activities compatible with the features of AFS companies. Subcategories and inventory indicators will be defined later, following the approach indicated by Luthin et al. (2023).

1.4.6 Improvement and communication strategies

The last step allows companies to both identify improvements to the existing CE strategies but also helps them in communicating the circular value generated to include in sustainable reporting.

1.4.6.1 Circular and Sustainable improvement areas of action

The adoption of circularity must be seen from a transformational perspective, as implemented strategies always offer room for improvement. The framework allows companies to monitor what was done and act in case of adverse trends.

Evaluating the performance and efficiency of the implemented approaches is crucial in the transition to a more circular and sustainable operating model. On the other hand, this highlights possible improvement strategies, be they internal, e.g. through process efficiency, or external, e.g. by developing new collaborations aimed at valorizing waste and by-products.

The subsection proposed here was adapted to the AFS from the study by Arana-Landin et al. (2023), which gathered improvement strategies for companies to move towards CE management. The list of potential circular practices is in Table 4.

Table 4: Examples of circular strategies displayed per area of circular action. Adapted from Arana-Landin et al. (2023).

Area of circular action	Potential circular strategy
Sustainable supply	Selection of local agri-food producers. Selection of suppliers for which the production units are located close to the deposits. Preference for suppliers that use organic and renewable inputs, e.g., organic fertilizer instead of mineral, do not use GMO.
Ecodesign	Designing packaging according to its capability to preserve the product during storage but also being environmentally less impactful.
Industrial symbiosis	Development of partnerships with other actors focused on waste and by-product valorization, e.g., sharing of organic waste with local farmers to substitute chemical fertilizers, using livestock companies' manure and sewage as input in anaerobic digestion, generating electricity and heat that could be used by both.
Responsible consumption	Communication with customers to inform their choice, e.g., through labelling systems. Sensibilizing employee, e.g., through workshops and informative events.
Life extension	Recovery of materials and elements to generate, e.g., bio-methane and fertilizer
End of their useful life	Increasing waste recovery, e.g., improving the recyclability of packaging, reducing the use of different materials for the same product, treating wastewater, reusing organic waste as fertilizer.

The list here proposed is not exhaustive but gives an example of potential strategies targeted for the AFS. Nevertheless, the above strategies are general suggestions which will first have to be evaluated as indicated in section 4.3 to assess their actual sustainability.

1.4.6.2 Circular value creation in sustainability reporting

By the end of the framework, companies will have gathered information potentially facilitating dialogue with stakeholders and financial institutions, as they can align the value created by the company with the criteria and recommendations provided in reporting. Corporate sustainability reporting should disclose the company's contribution to the environmental and social goals identified within the broader sustainability performance context. However, there is no clarity about what kind of CE-related information the report should include. According to the author, to integrate circularity into reporting, at least the CE strategy description and goals' contribution should be disclosed (adapted from Opferkuch et al., 2023). Thus, companies wishing to introduce CE into their sustainability reporting can use the information collected through the framework. Operatively, companies should first clarify their strategic targets as evidenced from the maturity self-assessment and based on circularity principles indicated by BS8001, (2017) (section 4.4.2.), and then explain the implemented strategy (section 4.4.3), pointing out the area of implementation of circularity, describing the practice adopted in terms of inputs, outputs and processes, and associating it with one or more strategies of the 10 Rs framework, as well as indicating critical stakeholders involved and the presence of possible partnerships. Secondly, companies indicate what environmental and social targets they want to pursue and finally report the outcomes of the KPIs, and circularity indicators selected to share their positive contribution to the goals defined. For the report itself companies have guidelines available like the Global Reporting Initiatives, however, this check list should help them to better frame their circular strategy.

For example, consider the cooperative Fattoria della Piana (described in Chapter 4) that uses its organic waste as input for energy production via anaerobic digestion. In this case, the cooperative would report that it adopts CE in eco-design and industrial symbiosis areas. It would indicate as input the waste used, e.g. litter, straw, manure, as process the anaerobic digestion, as output energy and digestate and associated to a Recover strategy (R10). They would indicate as key partners local AFS companies with which they have already established a collaboration based on the delivery of organic waste to feed the digester and the give back of digestate to use as fertilizer. Focusing only on the environmental targets at this stage, the company may select all or just some of the goals, e.g., it may select as target the Climate change mitigation, measured as 'net emission of GHGs', expressed in terms of kg CO_2, information available when conducting an LCA considering Global Warming Potential as an impact category. Regarding the circularity target, the selection of the circularity indicators depends on the circular strategy adopted by the company, namely by the inputs and outputs used or generated and previously indicated e.g., in this case, the main aspects to consider would be as output the energy balance and the nutrient recycling, while as inputs the efficiency of waste degradation. Thus, should select indicators focused on energy, soil, and waste areas. Thus, the company would include all the relevant information on the checklist.

1.4.7 Validation results

During the interviews, companies gave their feedback on each step of the framework and, at the end of the session, on its overall structure, adding possible ways of improvement. Each participant had to point out the level of clearness, the capacity to address the identified gap and application feasibility. The feedback structure was based on close-ended questions articulated according to a three-level Likert scale.

The maturity assessment step received overall positive feedback from the companies for its clarity, usefulness in addressing the framework goals (section 4.3), and feasibility according to the respondent's experience. The circularity implementation step was positively evaluated by companies for clarity, usefulness, and feasibility. The CE assessment step received again overall positive feedback. However, the responses on the feasibility of this step were more diversified, going from not feasible (n=1) to very feasible (n=1). The assessment of non-feasibility was later clarified by the company and was due to the time and effort-consuming nature of the collection of data for the measurement of CE, a perception particularly related to the life cycle approach methodology. The positive contribution step received a positive evaluation in terms of clarity, usefulness, and feasibility. The final step, improvement, and communication was positively evaluated in terms of clarity, efficacy and feasibility by the respondent companies.

The overall framework received positive consideration from the companies for clarity and usefulness. All the respondents claimed that they would apply the framework to their businesses. It was defined as “a way to “organise” and measure the impact of current practice and to identify new opportunities in a systematic procedure” (*Company#1, Large*). However, smaller companies are still cautious “It is very useful, although there are some steps we need to evaluate in terms of effort and benefits, like LCA” (*Company#2, Small). T*he framework implementation was considered feasible by all except one medium-sized company, which defined the framework as a clear and effective method to contextualize, assess and communicate circularity. The difficulty lies in uncertain time investment for data collection which makes it difficult to plan. However, as the company said, CE assessment will be required by the market and could be a potential entry barrier in the future. The general positive feedback received from the validation phase did not require modifying the framework at this stage.

1.5 Discussion and conclusions

The framework presented aims to guide companies of the AFS to measure and communicate the circular value generated. It is articulated in five steps: i) first companies self-assess to what extent they have embraced circularity principles into their business strategy through the maturity assessment stage, evaluating which aspects require additional improvements and setting their strategic targets in terms of circularity; ii) secondly, they clarify where and how they have implemented circular strategies, through the CE assessment stage; iii) following, in the CE assessment, they measure their level of circularity with specific indicators targeted for the food context and adopt the life cycle approach to assess the overall environmental, economic and social performances associated to their circular strategies, evidencing potential hotspots; iv) then they use the data collected to measure KPIs able to express their positive contribution to the environmental and social goals posed by the EU and social taxonomy, and v) finally, in the Improvement and communication stages, the hotspot analysis evidenced aspects to improve, so the framework presents possible improvements strategies based on the areas of action depicted by the XP X30-901 standard (AFNOR, 2018) but also offers a practical checklist of elements to include in the sustainability reporting to disclose the circular value created.

The assessment, based on the combined action of circularity indicators developed for the AFS and life cycle approaches allow to measure the circularity of the strategies implemented but also to check the environmental, economic, and social impact associated with those strategies. Their combined use is recommended given that a possible misalignment between the results of circularity assessment and LCA may arise (Rigamonti and Mancini, 2021). LCA was conceived for measuring on a cradle to grave perspective, thus not capturing the sense of recirculation of inputs and waste which characterizes CE and for this reason, LCA should be considered a complementary approach to CE assessment and not the primary one (Samani et al., 2023). Thus, an approach based on both LCA methodology and circularity indicators potentially generates a more precise vision of the critical points and possible margins for improvement in practices. The modularity and adaptability of the framework make it a valuable tool also for Small and Medium Enterprises (SMEs), since they can choose the configuration that is most suited for their activities and for the scope of their assessment (e.g., conducting a simplified LCA, or a carbon footprint). Furthermore, the use, where possible, of PCR ensures a greater level of reliability and comparability of results, paving the way for labelling mechanisms such as the EPD, an ISO type III Environmental Declaration based on LCA methodology. Consumers indeed trust environmental labels and declarations, since consumers consider them valid tools to deliver credible and viable information (Van Lagen et al., 2021). Moreover, future developments of the framework may focus on aligning the KPIs to the life cycle thinking.

Contrary to other proposals (Coluccia et al., 2023), this framework not only guides companies in evaluating circular strategies but emphasizes communicating the generated value to stakeholders. Raising awareness and effective communication are crucial, given the practical nature of the circular economy as an element of environmental sustainability. Companies must convey implemented initiatives, emphasizing their impact on their performance and the community. Communicating circularity internally fosters awareness among employees (Roos Lingreen et al., 2022) and externally enhances transparency, potentially improving company reputation and attracting new clients (Opferkuch et al., 2023).

The framework is significant as companies in the sector currently lack developed reporting forms that include circular economy principles (Falkenberg et al., 2023). With the introduction of CSRD and EU Taxonomy, companies will need to communicate circular and sustainable strategies, mitigating the risk of CSR reporting becoming a competitive barrier. Multinationals setting high codes of conduct may challenge suppliers in adapting to remain in the supply chain (Becchetti et al., 2022).

Additionally, the framework aligns with two of the three SFDR requirements for sustainable investments. Future expansions will include the remaining requirements, i.e., good governance. Quantifying and communicating the financial value created by CE is crucial for the sector, addressing barriers to implementation and measurement. The framework aids in communicating with financial stakeholders, providing a tool to gain support and overcome financial investments required by CE, especially during the implementation phase.

The validation of the framework through interview sessions with companies in the sector already implementing circularity showed a positive evaluation. All companies involved agree on the usefulness and clarity of the framework, although SME companies are still concerned about the time required for measuring CE.

Despite its potential, the framework is under development and requires further improvement, especially regarding the social and financial component. The consensus on the social value creation capacity of CE is lacking, hindering the identification of social boundaries and potential. Challenges and limitations are inherent, including potential misalignments between LCA and circularity metrics due to underlying assumptions. The framework demands data and expertise in various LCA-related methodologies, necessitating collaboration among experts, researchers, and industry practitioners. Finally, the framework still needs to be tested on companies of the sector.

In conclusion, the proposed framework, besides still preliminary, not only facilitates the implementation and improvement of circular strategies for AFS practitioners but also stands as a valuable reference for future studies on Circular Economy assessment and reporting. As the CE landscape evolves, this framework provides a foundation for companies to navigate the complexities, contribute to sustainability objectives, and effectively communicate their circular achievements.

1.6 References

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Appendix

Table A1: Overview of circularity indicators per sustainability area, adapted from Poponi et al. 2022.

Indicators	Scope	Sustainability Area	Description	Reference
Aquatic acidification	Air	Environmental	Ambient air quality concentrations of oxides of nitrogen and sulfur to potential surface water acid neutralizing capacity (ANC) within a NAAQS framework.	(Borsato et al., 2019) (Ioannidou et al., 2020)
Global warming potential	Air	Environmental	Cumulative radiative forcing, both direct and indirect effects, over a specified time horizon resulting from the emission of a unit mass of gas related to some reference gas [CO2: (IPCC 1996)].	(Del Borghi et al., 2018) (Laso et al., 2018) (Abejón et al., 2020) (Ilija Djekic and Igor Tomasevic, 2018) (Ioannidou et al., 2020)
Photochemical oxidant creation potential	Air	Environmental	Quantifies the relative abilities of volatile organic compounds (VOCs) to produce ground level ozone	(Abejón et al., 2020) (Ioannidou et al., 2020)
Particulate matter formation	Air	Environmental	Harmful effect on human health caused by emissions of particulate matter and its precursors (e.g. NOx, Sox, NH3)	(Ioannidou et al., 2020)
Agriculture total Emission	Air	Environmental	Total emissions from agricultural production	(Vasa et al., 2018)
Ozone layer depletion potential	Air	Environmental	Ratio of the global loss of ozone (i.e., integrated over latitude, altitude, and time) from that compound at steady state per unit mass emitted relative to the loss of ozone due to emission of unit mass of a reference compound, usually taken as CFC-11 (CFCl3) (Wuebbles, 1983; Fisher et al., 1990; Solomon et al., 1992)	(Abejón et al., 2020) (Ioannidou et al., 2020)
Human toxicity potential	Air	Environmental	Potential harm of a unit of chemical released into the environment, is based on both the inherent toxicity of a compound and its potential dose	(Del Borghi et al., 2018) (Ioannidou et al., 2020)

Indicators	Scope	Sustainability Area	Description	Reference
Green Water Footprint	Water	Environmental	Use of rainwater that remains in the roots	(Borsato et al., 2019)
Blue Water Footprint	Water	Environmental	Water that comes from irrigation and is incorporated by the plants	(Borsato et al., 2019)
Grey Water Footprint	Water	Environmental	The volume of water needed to dilute pollutants until water quality standards are restored	(Borsato et al., 2019)
Total area Equipped for irrigation	Water	Environmental	Area with direct access to water supplies	(Vasa et al., 2018)
Water use	Water	Environmental	Water used as an input by the agri-food sector	(Pagotto and Halog, 2016)
Water scarcity index	Water	Environmental	Ratio of water consumed to available water	(Del Borghi et al., 2018)
Eutrophication potential	Water	Environmental	Increase in aquatic plants due to excessive release of nutrients from 198ertilization (e.g. nitrogen and phosphorus)	(Laso et al., 2018) (Abejón et al., 2020) (Ilija Djekic and Igor Tomasevic, 2018) (Ioannidou et al., 2020)
Marine eutrophication	Water	Environmental	Reaction of a marine ecosystem to an excessive availability of a limiting nutrient	(Ioannidou et al., 2020)
Freshwater eutrophication	Water	Environmental	Excessive growth of aquatic plants or algal blooms, due to high levels of nutrients in freshwater ecosystems such as lakes, reservoirs and rivers	(Borsato et al., 2019) (Ioannidou et al., 2020)
Freshwater ecotoxicity	Water	Environmental	Heavy metal emissions to the freshwater from the comminution-beneficiation process and phosphorus associated with the water treatment processes resulting from the comminution-beneficiation process	(Del Borghi et al., 2018) (Borsato et al., 2019) (En15804 + A1); (Borsato et al., 2019)(EN15804 + A2)
Fertilizer consumption	Soil	Environmental	Amount of plant nutrients (nitrogenous, potash, phosphate) used per unit of arable land	(Vasa et al., 2018)
Use of pesticides	Soil	Environmental	Annual agricultural use of total pesticides in active ingredients. The sum of active ingredients is divided by the area of cropland	(Vasa et al., 2018)

Indicators	Scope	Sustainability Area	Description	Reference
Area under organic farming	Soil	Environmental	Land that is cultivated organically	(European Commission, 2016) (Priyadarshini and Abhilash, 2020) (Vasa et al., 2018)
Gross nutrient balance on agricultural land – phosphorus	Soil	Environmental	Degree of presence of the nutrient in the soil, defines the impact of agricultural practices on soil quality	(European Commission, 2016)
Gross nutrient balance on agricultural land – nitrogen	Soil	Environmental	Degree of presence of the nutrient in the soil, defines the impact of agricultural practices on soil quality	(European Commission, 2016)
Acidification potential	Soil	Environmental	Acid deposition of acidifying contaminants on soil, groundwater, surface waters, biological organisms, ecosystems, and substances	(Laso et al., 2018) (Abejón et al., 2020) (Ilija Djekic and Igor Tomasevic, 2018) (Ioannidou et al., 2020)
Average carbon content in the topsoil as % in weight	Soil	Environmental	Soil quality measured by the presence of carbon	(Vasa et al., 2018)
Agricultural machinery, tractors	Energy	Environmental	Number of agricultural machinery use in the agri-food sector during the reference year	(Vasa et al., 2018)
Bioenergy production as a % of renewable energy	Energy	Environmental	Bioenergy produced for the agri-food sector out of total renewable energy produced	(Vasa et al., 2018)
Wood fuel production	Energy	Environmental	Fuelwood or firewood (in log, brushwood, pellet or chip form) obtained from natural or managed forests or isolated trees. Also included are wood residues used as fuel and in which the original composition of wood is retained. Charcoal and black liquor are excluded.	(Vasa et al., 2018) (UNSD, 2018)
Energy selfsufficiency indicator	Energy	Environmental	Capability of the system to produce an amount of energy necessary for its operation	(Sgarbossa and Russo, 2017)
Recovery of energy by using waste	Energy	Environmental	Amount of energy produced by waste recovery	(Sgarbossa and Russo, 2017)
Energy required	Energy	Environmental	Amount of energy needed for waste recovery	(Sgarbossa and Russo, 2017)

Indicators	Scope	Sustainability Area	Description	Reference
Total Energy consumption	Energy	Environmental	Direct energy used	(Vasa et al., 2018) (Kucukvar et al., 2019)
Cumulative Energy Demand indicator (CED	Energy	Environmental	Amount of direct energy (conventional fuels) and indirect energy (fertilizers, pesticides, machinery) needed for the agri-food production	(Ghisellini et al., 2016)
Use of primary energy	Energy	Environmental	Direct energy used	(Abejón et al., 2020) (Ioannidou et al., 2020) (Pagotto and Halog, 2016)
Use of primary renewable energy	Energy	Environmental	Direct use of renewable energy	(Abejón et al., 2020) (Ioannidou et al., 2020)
Use of primary nonrenewable energy	Energy	Environmental	Direct use of non-renewable energy	(Abejón et al., 2020) (Ioannidou et al., 2020)
Nonrenewable energy demand	Energy	Environmental	Deamand of energy resources from the non-renewable origin	(Del Borghi et al., 2018)
Nutritional cost footprint	Waste	Environmental/Economic	Economic and environmental impact of wasted food	(Vázquez-Rowe et al., 2020)
Nutrient rich foods score	Waste	Environmental/Economic	Ratio of 9 nutrients that should be consumed to 3 nutrients that should be restricted	(Vázquez-Rowe et al., 2020)
Economic FLW indicator	Waste	Environmental/Economic	Economic valuation of food that becomes waste	(Vázquez-Rowe et al., 2020)
Waste sent to landfill	Waste	Environmental	The amount of waste from the food industry that is disposed of in landfills	(Pagotto and Halog, 2016)
PackagetoProduct	Waste	Environmental	Ratio of the environmental impacts of packaging to the packaged product	(Šerešová and Kočí, 2020)
Nutrient circularity indicators (carbon, nitrogen and phosphorus)	Waste	Environmental	Amount of component that extends its lifetime by providing a service in upstream processes compared to the amount of that component present in the collected (downstream) waste	(Cobo et al., 2018)
Recycling rates	Waste	Environmental	Amount of recycled waste from the food processing industry	(Pagotto and Halog, 2016)
Pesticides value	Cost, value, and productivity	Economic	Economic value of the Pesticides per unit	(Vasa et al., 2018)

Indicators	Scope	Sustainability Area	Description	Reference
Organic fertilisers value	Cost, value, and productivity	Economic	Economic value of the Organic fertilisers per unit	(Vasa et al., 2018)
Profitability indicator	Cost, value, and productivity	Economic	Assessing the cost-effectiveness of implementing an innovation for the CE	(Sgarbossa and Russo, 2017)
Total capital investment	Cost, value, and productivity	Economic	Total capital invested in the implementation of an innovation for the CE	(Sgarbossa and Russo, 2017)
Net present value of annual cash flow	Cost, value, and productivity	Economic	Difference between the present value of cash inflows and outflows of an investment for innovation	(Sgarbossa and Russo, 2017) (Ioannidou et al., 2020)
Cost of manufacture	Cost, value, and productivity	Economic	The costs incurred in producing a finished product include the costs of labour, materials and overheads	(Ioannidou et al., 2020)
Fixed capital investment	Cost, value, and productivity	Economic	Capital invested in fixed assets (e.g. plant)	(Ioannidou et al., 2020)
Minimum selling price	Cost, value, and productivity	Economic	Selling price that is not lower than the price incurred to make the product	(Ioannidou et al., 2020)
Payback period	Cost, value, and productivity	Economic	Time needed to recover the cost incurred for the investment	(Ioannidou et al., 2020)
Gross profit	Cost, value, and productivity	Economic	Difference between total revenue from sales and the cost incurred in purchasing materials	(Ioannidou et al., 2020)
Net profit	Cost, value, and productivity	Economic	The profit obtained from an activity net of costs incurred	(Ioannidou et al., 2020)
Value added	Cost, value, and productivity	Economic	Added value obtained from the activity	(Laso et al., 2018)
Production costs	Cost, value, and productivity	Economic	Cost of production	(Pagotto and Halog, 2016)
Total revenue	Cost, value, and productivity	Economic	Revenues generated	(Pagotto and Halog, 2016)
Child labor	Equality	Social	Exploitation of child labour	(Dammert et al., 2018)

Indicators	Scope	Sustainability Area	Description	Reference
Forced or compulsory labor	Equality	Social	Condition in which work is carried out involuntarily for various reasons (e.g. debt bondage, forced child labour)	(Simas et al., 2014)
Employment possibilities	Equality	Social	Creation of new job opportunities by adopting a circular model, both in terms of new staff and skills	(Sgarbossa and Russo, 2017)

Chapter 6: Conclusions

The aim of this dissertation, in line with the requirements of PON grant no. 2, was to examine the implementation and integrated measurement of circularity in the agri-food sector at the farm level. The following sections will first highlight the issues raised by the individual chapters and then a general reflection on the future of circularity in the AFS in light of recent policy developments.

1.1 State of the art of CE implementation in the Agri-food context (Chapter 2 – Paper 1)

In order to define the context of the research interest and identify the main existing gaps, the first research question investigated was:

"*What can we learn from inter- and intra-organization practices and experiences of CE in the Agri-food sector to assess the circular maturity of the sector?"* The study performed a systematic and bibliometric literature review which revealed 43 articles and 162 circular practices on the topic. The analysis revealed a growing interest in circularity in the agri-food context. In analyzing the examples of circularity reported, the preponderance of conventional circular practices in the sector suggested how the agri-food system has already introduced the principles of circularity, which led us to assume its relative maturity. In any case, only the combination of traditional knowledge with incrementally innovative practices, i.e. based on improving existing knowledge, considering both the technological and socio-organizational components, can guide the sector towards the valorization of CE. The presence of conventional circular practices was considered a sign of maturity in terms of circularity; however, it may relate to the limited structural elasticity of the sector to innovation. When analyzing instead, the relationship between CE and sustainability, the boundary here also seems blurred. CE is almost exclusively associated with the environmental dimension, with a few links to the economic sphere and rarely social. Finally, to improve social sensibility, the sector should increase community engagement through bottom-up initiatives aimed at stimulating circular and sustainable actions. However, the analysis was focused on case studies reported in literature, thus it is necessary to understand how practitioners of the sector perceive and adopt circularity in their business.

1.2 CE assessment and implementation in the agri-food sector (Chapter 3 – Paper 2)

In order to assess how the principles of circularity were introduced by companies in the sector and translated into actual strategies, as well as how companies monitored them, it was decided to analyze a sample of companies in the agri-food sector that already implemented CE in their business. Portugal context was used because of the relevant role of the AFS in the Portugues economy and the initiatives in promoting circular solutions to tackle its challenges. Moreover, during the secondment period at Universidade Aberta in Lisbon, the support of the research center *GreenUPorto* allowed us to identify a valuable sample of companies interested in CE and operating in the AFS.

How do companies of the AFS implement and assess CE?

The study is based on a survey and nine interviews to deepen some of the themes that emerged during the questionnaire. Analysis of the 31 responses to the questionnaire revealed that most of the companies considered the circular practices implemented by their company to be of an incremental innovation nature. Assessment is limited in the sample, although several companies that do not monitor CE state that they use tools such as KPIs and life-cycle approaches to monitor their activities. The companies interviewed confirm the limited interest in measurement, often perceived as a secondary element.

From a social point of view, the CE promotes the development of community initiatives through services and awareness-raising initiatives both within the company and externally, as well as the development of interesting collaborative initiatives with start-ups and other entities in the surrounding areas. The financial cost is an obstacle in terms of initial investments, but if the company can incorporate circularity into a long-term strategic plan, it may have more opportunities to attract new investors and new market segments. In conclusion, the study asserted the difficulty of companies in the sector in assessing and sharing the value generated from the implemented CE initiatives. Thus, designing a framework able to guide companies of the sector towards an efficient assessment and reporting of circularity could increase their interest towards circularity.

1.3 Assessing circularity and sustainability in the agri-food sector (Chapters 4 and 5 – Paper 3)

As a result of the limited focus on measuring CE found in companies in the AFS and their difficulties in reporting the impact of the strategies implemented to stakeholders, an attempt was made to understand:

How can companies of the AFS assess and monitor the circularity and sustainability of their activities?

To answer the research question, first a case study analysis was carried out to identify an efficient assessment approach to monitor the circular performances adopted by an exemplar case of circularity ad sustainability in the food context, then outcomes were then used as input in designing a framework to guide companies of the sector towards an effective assessment and communication of the circular strategies implemented.

The case study analysis was performed on the dairy cooperative Fattoria della Piana, a best case of circularity in the Italian context. Specifically, the present preliminary analysis considers the AD-CHP as the core of the cooperative's ecosystem, which enables to close energy and waste loop of the cooperative and is the center of the symbiotic relations with partner companies. To monitor the environmental performance of the implemented circular strategies, the study proposed an approach combining circularity indicators with LCA. The two approaches lead to good environmental performance, especially considering the products avoided, but to a variable circularity judgement based on the boundaries of the system considered. To provide an effective assessment of CE in environmental terms divergent but complementary tools, such as the LCA, which is suitable for measuring overall performance, and indicators, which can define the circularity level of a system. The two approaches provide different but complementary perspectives on the problem to limit the risks of the rebound effect. However, the circularity of a system is affected by the instruments and the perspective of analysis, which require case-by-case considerations. The present study is preliminary since the final objective is to evaluate all the cooperative chains. Moreover, circularity implies a systemic perspective, i.e. it displays social, environmental, and economic impacts. Future developments of the analysis will integrate these two perspectives within the framework of the company's circularity assessment through LCC and S-LCA, combined with appropriate indicators.

The framework design was meant to support companies in the sector in evaluating and reporting the circular strategies implemented. The aim is to offer a valid guide to enhance the experiences of CE. Using the previously collected information on performance, some KPIs are calculated to verify the contribution of the implemented strategies to the achievement of social and environmental objectives. Finally, it offers possible circularity-driven improvement strategies, as well as support in the introduction of the CE in the sustainability report or external reporting through a checklist.

1.4 Limitations of the study

The present research thesis tried to map and explore how circularity is implemented and assessed at the company level in the AFS, proposing a tool to guide companies in assessing and reporting the circular practices implemented. However, some limitations due to the methodological choices are present. First, the search criteria for the literature review may have excluded potential interesting contributions, e.g., from grey literature. Moreover, it was focused on the micro and meso level of analysis, thus neglecting the macro perspective (e.g., national level), which may be a driver or a barrier to companies' interest in CE. Secondly, the empirical analysis was based on a selected sample of Portuguese companies implementing CE was exploratory and based on a reduced sample of companies. This provided interesting insights on how to implement and measure CE in the sector, including also social and financial aspects in the analysis. However, enlarging the sample or proposing comparative studies in other EU countries would be interesting to improve the generalization of the outcomes. The case study analysis presents preliminary results concerning the AD-CHP plants from an environmental perspective. Nevertheless, the cooperative Fattoria della Piana is a best case of CE and industrial symbiosis in the Italian context, thus the overall goal is to evaluate all of its chains encompassing the cooperative enlarging the perspective of analysis also to the social and economic profile, through LCC and S-LCA method combined with appropriate indicators able to capture the level of circularity of such aspects. Finally, the framework is still under development, so some limitations exist. First, there is a need to better address the social targets, giving more detail in the S-LCA analysis and identifying specific KPIs. Moreover, an initial validation phase with (3 Portuguese and 1 Italian) companies implementing CE in the AFS was carried out and gave positive feedback on the overall framework; however, a test on a real case study would be crucial to assess its validity. One potential challenge is the required capacity to master the life-cycle methods (LCA, LCC and S-LCA) to adopt the framework.

In conclusion, the present preliminary framework could guide companies of the AFS towards improving the circular strategies implemented but also stands as a valuable reference for future studies on CE assessment and reporting.

1.5 Policy, operational and methodological implications

As Peter Drucker concluded: 'You cannot manage what you cannot measure', especially about circularity. If circularity does not align with sustainability, there is a risk of burden-shifting; therefore, a combined approach of LCSA and specific circularity indicators ensures that companies choose an effective strategy that is good for themselves, society, and the environment. Policymakers are key players in supporting companies in the transition towards sustainable development. However, it is difficult to navigate the concepts of CE and sustainability and to grasp all the nuances that a circular model implies in complex sectors such as AFS. The abundance of available CE metrics increases the risk of greenwashing, understood as a form of "Disinformation disseminated by an organization to present an environmentally responsible public image... but perceived as unfounded or intentionally misleading" (Concise Oxford English Dictionary). Therefore, measuring the circularity of a strategy and its environmental, economic, and social impacts is crucial to avoid greenwashing. The plethora of metrics available for assessing CE makes companies prone to choose the indicators that best describe their image, thus providing a framework that can synthesize what is already available and avoid complete additional complexity for companies and policymakers. It is still difficult for companies in the sector to implement CE due to a lack of financial resources, hence the importance of promoting initiatives or rewarding mechanisms for those companies that implement the model correctly (i.e. according to the pillars of sustainability).

Therefore, policymakers should design initiatives calibrated to the characteristics of the CE and contextualized in the AFS. The framework presented in Chapter 5 fits into this discourse; policymakers could adopt the proposed approach and, for example, identify threshold levels or a delta of 'positive change' for KPIs used by companies to measure their positive contribution and thus identify companies deserving support, e.g. through subsidies or tax relief. This could help promote the development of CE models in the sector, with benefits for the whole system, given the crucial role of AFS. In addition to providing a valid strategy for the evaluation and reporting of CE to AFS companies, the modularity of the framework makes it a tool that can be updated according to forthcoming regulations simply by adding more modules and not by changing the complete structure of the framework.

1.6 Food for thoughts

1.6.1 Future studies

In the circularity context, a relevant topic which need further study is the protection of biodiversity, defined as "the variability of living organisms and the ecological systems in which they live" (United Nations Environment Program 1992) by the UN Convention on Biological Diversity. It is mainly human activities related to the use of materials and resources, e.g. land management, that lead to the reduction of biodiversity. To halt the loss and restore ecosystems by 2030, the Green Deal launched the EU "Biodiversity Strategy" (European commission, 2020). Nevertheless, safeguarding biodiversity is a cross-cutting issue linked to various initiatives such as the "Circular Economy Action Plan" (European commission, 2020). It is necessary to act on the entire production and consumption system to combat this phenomenon. In this context, the CE can be a valuable ally, thanks to its focus on changing the current production and consumption system to promote efficient resource management. In the fight against biodiversity, the AFS plays a predominant role since it is responsible for 50% of the anthropogenic pressure on biodiversity. Specifically, the cultivation and extraction phases are particularly impactful, firstly due to changes in land use and secondly due to climate change.

On this issue, circularity and biodiversity converge through regenerative agriculture strategies. The regenerative agriculture, in line with the Farm to Fork initiative (European commission, 2020) and the principles of the CE, aims to increase soil productivity through reduced inputs such as fertilizers, pesticides and mechanical tillage. A concrete example is organic fertilizers, which can be obtained either through composting techniques for agricultural waste or organic waste in general or through anaerobic digestion processes, which produce biogas as the main product and digestate as a co-product used as a fertilizer. Studies (Sitra, 2022) have shown how biodiversity circularity through policy- and business-led interventions can contribute to halting biodiversity loss by 2035 and restoring it to pre-2000 levels. In this context, acting on the AFS can significantly contribute to restoring biodiversity with beneficial effects for the entire ecosystem (Garzarella et al., 2023). Moreover, given the presence of the UNI/TS 11820:2022 standard which already identified a valuable set of indicators to measure CE but is not sector-focused, future studies could assess circularity according to standard testing its capacity to capture the complexity of the food system, aiming at circularity overall score for the AFS.

1.6.2 Recommendation for Practitioners

However, in terms of recommendations for practitioners, the implementation of CE and regenerative models cannot disregard the current socio-political context of the AFS. Climate change is real, especially for the agricultural sector. During the last few years, extreme weather events such as wildfires and droughts have swept through Europe, increasingly affecting food production. To limit such phenomena, the Farm to fork strategy focuses on halving the use of pesticides by 2030, reducing fertilizer use by 20 per cent, increasing the proportion of non-agricultural land and increasing organic production to 25 per cent of all agricultural land in the EU. However, the European Green Deal is a recent source of tension. And yet, the sector is at the heart of ethical and social issues. The costs of farmers and breeders have risen considerably over the years, especially following the war in Ukraine, with significant increases in energy, fertilizer and transport costs. For instance, according to Eurostat (2023), farmers suffered an average reduction of 9% between the third quarter of 2022 and the same period of the previous year. In addition, there is an imbalance within the agri-food chain, where large retailers impose low prices on producers despite prices rising while yields fall due to adverse weather events. The sector is currently supported by public subsidies and grants to alleviate the income of farmers. Even the Cap, an important source of subsidies for the sector that has ensured European food security for the last 60 years, for the 2023-27 seven-year program sets itself objectives in line with the Green Deal, such as the reduction of fertilizers and pesticides. The CAP is, however, accused of favoring economies of scale, i.e. favoring larger companies. Against this backdrop, governments began to enact measures to achieve the goals of the Green Deal; hence, the industry revolts. Farmers and breeders complain about the contradictions of a system that favors demand for cheap food but also climate-friendly processes (The Guardian, 2024.02.02).

In principle, farmers are not opposed to the measures imposed by the Green Deal; what they are opposed to is not being an active part of that transition. It is necessary to integrate practitioners into European agricultural policies to find collaboration for a more sustainable future. The strong lack of consensus in the agri-food sector prompted the European Commission to take a step back, unblocking public incentives to farmers and withdrawing the legislative proposal on pesticides. European Commission President Ursula von der Leyen acknowledged the need for a collaborative approach and dialogue (Il Giornale d'Italia, 2023-02.07).

Specific sustainability reporting standards will be developed by the EFRAG for single sectors, and “Agriculture, Farming and Fisheries”- currently in the early drafting phase, are included. Sustainability reporting could be a significant barrier to entry for companies in the sector if not properly calibrated. It is hoped that this will allow for requirements adapted to the characteristics and needs of the sector. Thus, a regenerative and circular path is possible, but a bottom-up approach based on more dialogue between institutions and various stakeholders will be needed to define the objectives and targets to achieve.

1.7 References

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