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A framework to measure circularity performance in the agri-food sector

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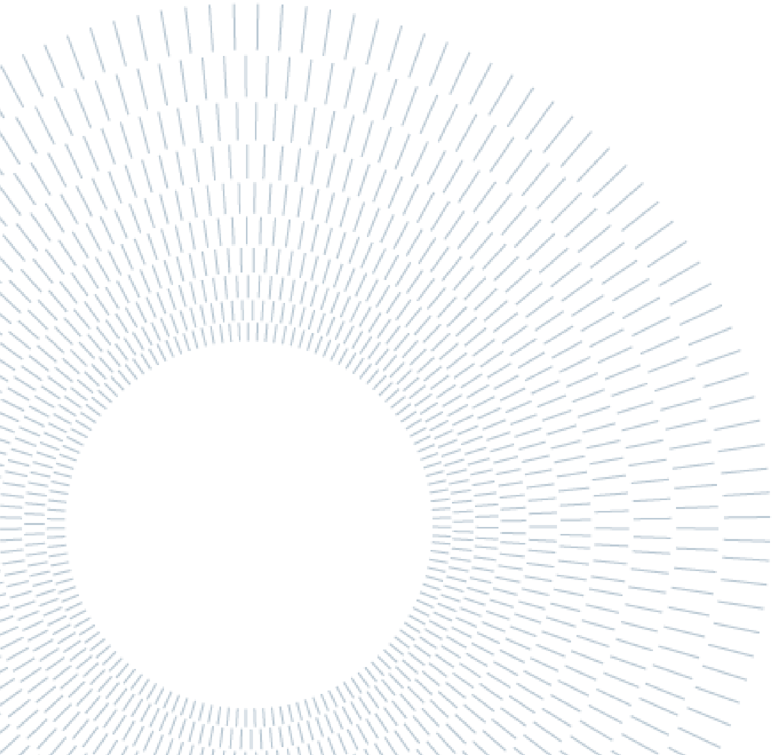


Abstract

Circular Economy is gaining increasing relevance among industries, institutions and researchers as a possible solution to pursue environmental, economic and social sustainability in the future, which represents Sustainable Development. More specifically, out of all industries, the agri-food sector can benefit from the implementation of circularity strategies to address the growing resource consumption issues and the ensuing problems related to the food demand. However, reviewed literature highlighted that the current circular evaluation methodologies lack accuracy and clarity.

This study tries to fill this gap by proposing a pool of specific circularity indicators to define a standardized framework. This dashboard can be helpful for decision-makers to guide agri-food businesses toward the evaluation and application of circularity. The indicators are classified based on two dimensions for obtaining a more integrated picture: the content of the metric and the impact it has. The first dimension is composed of clusters which refer to the specific features of the sector, they are 'air', 'water', 'energy', 'soil', 'waste', 'resource consumption' 'revenues', 'cost', 'social', 'effectiveness and productivity'. Instead, the second dimension includes the aspects assessed by the implementation of the metric, such as which sustainable element (economic, environmental, social), which level of analysis (nano, micro, meso, macro) and which R strategy (Reduce, Reuse, Recycle and Recovery) are impacted. Furthermore, a flowchart is proposed as a guide for choosing the best indicators according to internal and external needs and requirements.

The table, combined with filters and the flowchart, allows to obtain a simplified and unified guideline to be used in the decision-making process and thus encourages the adoption of circular practices.

Future steps should continue to update the dashboard, both adjusting the existing indicators and including new ones to try to represent the dynamism and needs of the sector.

Key-words: circular economy, assessment, circular indicators, agri-food, decision making support

Abstract in italiano

L’Economia Circolare sta acquisendo sempre più rilevanza tra le aziende, le istituzioni e i gruppi di ricerca in quanto rappresenta una possibile soluzione per il raggiungimento di un futuro sostenibile. Tra tutti i settori, l’industria agroalimentare in particolare può beneficiare dell’introduzione di pratiche circolari per far fronte alle sfide legate al consumo delle risorse e alle difficoltà che ne derivano dalla crescente richiesta di cibo. Tuttavia, gli studi scientifici analizzati rivelano come gli attuali metodi di misurazione non consentano una valutazione chiara ed accurata della circolarità di un processo.

Il lavoro proposto cerca di colmare questa lacuna presentando un insieme di indicatori di circolarità che guidino i decisori nel processo di crescita delle aziende agroalimentari verso modelli più circolari. Gli indicatori sono classificati su due dimensioni. La prima analizza le metriche sulla base del loro contenuto, dividendole nei seguenti cluster individuati a partire dalle caratteristiche del settore: ‘aria’, ‘acqua’, ‘energia’, ‘suolo’, ‘rifiuti’, ‘consumo di risorse’, ‘ricavi’, ‘costi’, ‘sociale’, ‘efficienza e produttività’. La seconda dimensione invece include gli aspetti impattati dall’implementazione dell’indicatore, i quali possono essere relativi alle dimensioni sostenibili (ambientale, economica o sociale), alle R strategies (Reduce, Re-use, Recycle, Recover) e livello di analisi (nano, micro, meso, macro).

In seguito, è stato proposto un flowchart che, sulla base delle necessità e dei requisiti interni ed esterni da rispettare, supporti il processo decisionale nella scelta dei KPI.

La tabella, insieme ai filtri e al flowchart, permette di ottenere delle linee guida semplificate e standard da poter utilizzare nell’adozione di modelli più circolari.

In futuro, il cruscotto sviluppato richiederà continui aggiornamenti degli indicatori esistenti e la possibile introduzione di nuove metriche per rispecchiare coerentemente la dinamicità e i bisogni del settore.

Parole chiave: economia circolare, valutazione, indicatori circolari, settore agroalimentare, supporto al processo decisionale

Contents

Introduction

In the context of a fast-growing population and diminishing natural resources, the agri-food sector has to face several challenges.

First, it has to satisfy food demand, also through the reduction of the disparity between food poverty and food wastage. Current data show a critical condition: while the global food demand is projected to increase by 35% to 56% from 2010 to 2050 (van Dijk M. 2021), between 702 and 828 million people worldwide have experienced hunger in 2021 and about one-third of food produced globally has been lost or wasted (FAO, IFAD, UNICEF, WFP and WHO 2022).

Moreover, nowadays food production and supply are responsible for more than one-quarter of the energy used worldwide (Del Borghi A. 2020), while food loss and waste account for 8 – 10% of global greenhouse gas emissions (FAO, IFAD, UNICEF, WFP and WHO 2022). Furthermore, agriculture is the world's largest consumer of freshwater resources (Ellen MacArthur Foundation 2019) and the primary cause of soil degradation (Watts J. 2017). From an economic point of view, several authors emphasize that avoidable food losses have a direct and negative impact on the income of both farmers and consumers, mainly linked to production and purchasing costs, as well as costs associated with the final disposal of food waste (Gustavsson J. 2011, Lundqvist J. 2008). Last, food waste also has social and moral implications (Salhofer S. 2008) highlighted by the disparity between food poverty and food wastage.

During the Food System Summit in 2021, the United Nations promoted the idea that making the food system more sustainable is one of the most impactful approaches to adopt in order to address the ethics problems as well as climate change and restore biodiversity issues. This new system has to deliver food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised, consistent with the concept of Sustainable Development (von Braun J. 2021).

In this scenario, Circular Economy is considered an effective solution to introduce into the agri-food sector by a wide number of authors and international organisations, since it allows to minimize the external inputs required, close the loops in production, reduce waste and emissions and utilise resources, raw materials and energy more effectively (Muscio A. 2020, Zadgaonkar L.A. 2022, Zhang X. 2013).

Implementation of a circular strategies is not enough. Companies need to be able to measure their circularity performance to ensure that strategies lead to true progress towards sustainable production and consumption.

However, the most popular assessment methods in literature are quite general and do not consider important sector-specific aspects. They also tend to aggregate different areas into a single metric, as including the economic, environmental and social pillars together (Calzolari T. 2022). If on the one hand these composite indicators allow adopting a synthetic and holistic perspective that also facilitates benchmarking, on the other hand, they do not allow going into detail and understanding what specific areas need improvement. However, when it comes to simple indicators that are more focused on specific aspects, corporate decision-makers are overwhelmed by a myriad of indicators present in literature and may be lost when choosing the circularity indicators best suited to their context (Iacovidou E. 2017).

Therefore, the purpose of this study is to gather into a single database the most relevant circularity indicators applicable to the agri-food sector and to provide a guiding framework for selecting them to support decision-making processes.

From a procedural point of view, the paper is structured as follows. First, a general literature review on sustainability and Circular Economy and their assessment methodologies has been conducted and reported in chapter 1. After an explanation of the research methodology, the relationship between sustainability and Circular Economy is clarified, followed by an overview of CE principles, strategies, advantages and challenges. Therefore, an analysis of sustainability and circularity assessment, with their respective definitions, purposes, benefits and drawbacks and their different methodologies is presented. Last, an overview of the main indicators' classifications found in literature is provided in order to clarify the state-of-art.

A second literature review more focused on the agri-food sector is addressed in chapter 2. It starts with a brief description of the sector and all the steps in the agri-food supply chain, and then how sustainability and Circular Economy are applied and measured in this industry has been analysed. A series of trends highlighting the importance of adopting more circular and sustainable systems are reported here, followed by an overview of the main CE implementation strategies in the agri-food sector. The entire literature review is then closed with an analysis of sustainability and circularity assessment of food production systems, with an overview of the main international recognized frameworks such as SAFA (Sustainability Assessment of

Food and Agriculture Systems), the Water-Energy-Food nexus and the Food Waste Hierarchy.

The emerging research questions are presented in chapter 3, they aim to understand which circularity indicators apply to the agri-food sector and how companies can orient themselves in their choice of indicators. To fill this gap, the most common circularity indicators in literature have been collected in a framework and it has been developed a guiding flowchart to select indicators to support decision making. The indicators have been selected and evaluated based on specific characteristics, goals and subjects. They were then classified according to their impact on the three pillars of the Triple Bottom Line (Environmental, Social, Governance), the food CE strategies (Reduce, Reuse, Recycle, Recover) and the level of analysis at which they can be applied (nano, micro, meso, macro). Finally, all the indicators dealing with common topics have been clustered in the same packages in order to highlight the main fields explored by the indicators in the database.

Chapter 4 is dedicated to the presentation of the final framework of indicators and the quantitative analysis performed on them, while instead the flowchart to guide companies to select indicators according to their specific context is proposed in chapter 5.

Finally, chapter 6 drafts some conclusive remarks on this thesis, highlighting its limitation and proposing possible developments for this line of research.

1 Literature Review – Sustainability and Circular Economy

The goal of this chapter is to provide a clear picture of sustainability and circularity topics, in all their facets. Awareness on these themes is increasing and consequently so is complexity and confusion.

It starts with a Systematic Literature Review, presented in section 1.1. This stage is required for the development of the research questions and for the specification of the research flow to follow to address them.

Section 1.2 introduces the concepts of sustainability and Circular Economy, from their historical definition to the more recent applications and developed strategies. The evolution from linear to sustainable and then circular model is better addressed in paragraph 1.2.1, Circular Economy is then further developed in paragraph 1.2.2, where the core features, benefits and drawbacks are shown.

Once the most frequent visions are presented, the strategies to evaluate them are defined. Sections 1.3 and 1.4 present methodologies to assess respectively sustainability and circularity in organisations, highlighting the core characteristics and features. Finally, section 1.5 focuses on the analysis of a circular methodology by examining it in detail and classifying its characteristics.

1.1 Research methodologies

A Systematic Literature Review methodology is performed to show the main contributions that are pertinent to the research issues of this study through a methodical and transparent process. In this instance, the goal is to evaluate the state of the art of the sustainability and circularity assessment methods, with a special focus on indicators, applicable in the agri-food sector to measure performances.

In order to adequately report the main objective of this research, the literature evaluation was carried out in two stages. First, a detailed analysis of sustainability and circular economy concepts have been conducted and presented in sections 1.2, 1.3, 1.4 and 1.5. Chapter 2. reports the specific analysis of the agricultural sector, chosen for examination because of its significant relevance for the impact it produces in terms of sustainability. Both reviews are divided into four main steps: source identification; source selection; source evaluation; and data analysis (Maestrini V. 2017). Figure 1 illustrates the steps of the research process adopted.

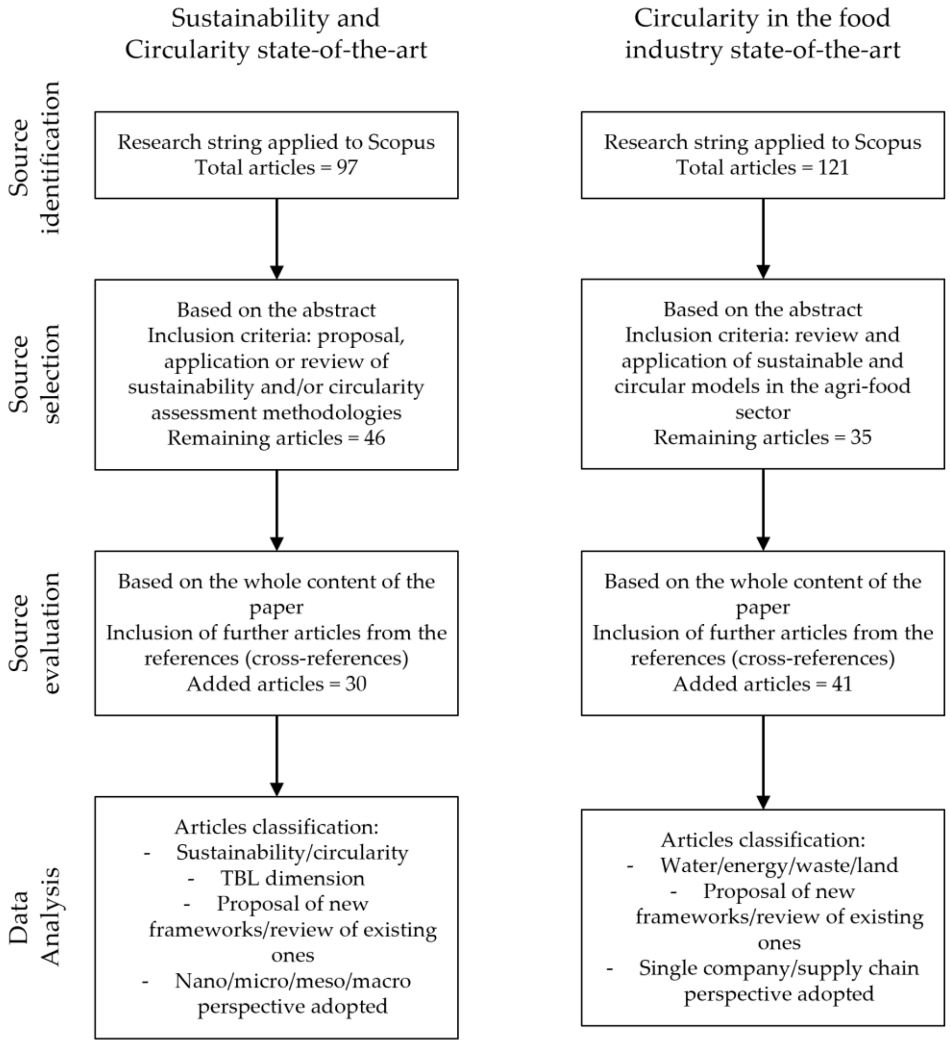


Figure 1 – Flowchart of Literature Review process

The peer-reviewed academic database SCOPUS has been used in the source identification step. The principal keywords and their synonyms have been used to create the search strings and searched for in the "titles, abstract and keywords" filter.

According to Moraga et al. (2019), terms such as 'indicator', 'index', and 'metric' are interchangeable, therefore they are all included in the search string as synonyms for the term 'key performance indicator'. So, the research string related to the assessment of sustainability and Circular Economy is:

TITLE-ABS-KEY(circular*) AND (TITLE-ABS-KEY(indicator*) OR TITLE-ABS-KEY(index*) OR TITLE-ABS-KEY(metric*)) AND (TITLE-ABS-KEY("sustainability performance*") OR TITLE-ABS-KEY ("sustainability assessment"))

97 articles are founded.

For what concern the second aspect, the goal is not only to understand how circular economy is present in the food sector in general, but also in the specific stages of the supply chain. For this reason, the research string contains references to the circularity and the stages of food supply chains. Consequently, the second part of the search string consisted of the terms 'production', 'processing', 'distribution', 'consumption' and 'disposal'. 121 articles are founded.

TITLE-ABS-KEY(agri-food) OR TITLE-ABS-KEY(food)) AND TITLE-ABS-KEY(sector) AND (TITLE-ABS-KEY("circular economy") OR TITLE-ABS-KEY(CE) OR TITLE-ABS-KEY(circular*)) AND (TITLE-ABS-KEY(assessment) OR TITLE-ABS-KEY("waste hierarchy")) AND (TITLE-ABS-KEY("food supply chain") OR TITLE-ABS-KEY(“food production”) OR TITLE-ABS-KEY(“food distribution) OR TITLE-ABS-KEY(“food processing”) OR TITLE-ABS-KEY(“food consumption”) OR TITLE-ABS-KEY (“food disposal”))

A preliminary selection procedure is carried out once the set of potentially significant publications had been determined. The following criteria are used to define the analysis's boundaries, minimizing the potential for bias when choosing.

Only journal or conference articles written in English, which are subjected to peer-to-peer review are considered. No limitations are applied to the search period to capture different conceptual CE methods since they have mostly been generalised as a result of the work done by the Ellen MacArthur Foundation (EMF).

The inclusion criteria presented now, concerning the analysis of the contents of the paper, are applied by examining only the abstracts. When these aspects did not provide clarity, reading the introduction and conclusion is also integrated.

Regarding the criteria of the first literature, included papers either propose, apply or review indicators or measurement frameworks for the assessment of sustainability and Circular Economy; or focus on bio-economy sector, i.e., industries that use biological resources from land and sea to produce, for example, food. With this inclusion criteria, articles with sustainability and circularity validation for specific sectors, completely outside the scope of analysis (such as construction, thermal, mining, …) are excluded.

The number of papers decrease because of the scanning process (from 97 to 46) obtaining articles that could contribute to creating a broad understanding of how sustainability and the circular economy are put into practise and assessed.

The aim for the other articles is still to obtain an overview, in terms of characteristics, strengths and weaknesses and areas of a possible implementation of sustainable or circular models in the food industry. So, inclusion criteria concern the choice of articles presenting a broad overview of the aspects of the sector, or the application of sustainable and circular models, without, however, going into too specific and limited case studies, which lose the overall vision. The remaining articles were 42.

The two members of the study team handle this phase independently and separately. Throughout this and the next phases, regular team meetings are held to compare the decisions made and guarantee that the procedure is rigorous. Each disagreement is individually reviewed to reach a consensus (Maestrini V. 2017). In the source review phase, articles that could not be completely dismissed with the utmost assurance have been included for additional analysis.

Once the sources had been identified, the evaluation phase proceed. The remaining articles are all accessible, so they have been read in their entirety and key recurring themes have been identified. These made it possible to create a classification of the articles, related to the type of assessment presented, which could be sustainability or circularity, with sustainability being further discussed as to which aspects were covered (economic, environmental or social); the presence of new frameworks or indicators; and lastly, the perspective adopted, whether a single company or a system view. These are the inclusion criteria of this second phase, and all the articles respected them.

The classification for agri-based papers is based on the specific resource covered in the discussion (water, waste, land, energy), the perspective adopted (single company or supply chain), the presence of existing methodologies or indicators to implement and assess circularity or the creation of new tools.

Furthermore, about 31 more publications for sustainability and 33 for the food sector have been discovered by cross-referencing. They have been examined against the inclusion criteria as part of this study, meeting the criterion specifications required and making them all eligible. The approach followed is Snowballing, the process of finding more publications by leveraging a paper's reference list or its citations. Snowballing might benefit from a systematic approach to looking at where publications are referred to and where papers are cited in addition to just looking at the reference lists and citations (Wohlin C. 2014).

Among the reviewed documents, some are not scientific and academic articles but instead they are reports from international organisations. For example, the literature on the food sector refer to publications of the Food and Agriculture Organisation of the United Nations (FAO), which provides a source of knowledge and information to help developing countries and countries in transition to modernise, improve agricultural, forestry and fisheries practices and ensure good nutrition for all. Instead, Ellen MacArthur Foundation provided useful insights about Circular Economy and its implementation and assessment.

1.2 Sustainability and Circular Economy: key concepts

The state-of-the-art sustainability and circularity themes are exposed in this paragraph, starting from their introduction to their development until the present days.

The transition from the current Linear Economy model to a Circular Economy one is increasing and so it is suggested to include it among the priorities inside a company strategy in order to make the future more sustainable. Climate change and many other sustainability issues that are affecting the planet are linked to the fact that the population is growing exponentially, as well as consequently also resource consumption, CO_2 emissions and environmental impacts. According to the Global Footprint Network, today humanity uses the equivalent of 1.75 Earths to provide the resources consumed and absorb waste (Global Footprint Network 2022). This means that people consume more ecological resources than our planet can regenerate through its natural processes. In other words, there are no longer enough resources to run the future sustainably. Therefore, it is extremely important to understand how to decouple population and economic growth from the use of natural resources (Zhang X. 2013, P. D. Kravchenko M. 2019).

The Linear Economy relies on a Make – Use – Dispose pattern, thus implying always use of new materials to produce new products. This increases not just the waste level, but also the amount of energy, resources and toxic emissions related to the extraction of new raw materials. Instead, Circular Economy aims to retain as much value as possible from products, parts and materials, relying on "a regenerative system in which material input and waste, emissions and energy leakages are minimized by slowing, closing and narrowing the resource loops" (Geissdoerfer M. 2017). So, this model aims to increase efficiency by producing the same level of output with less input and waste, generating not just environmental benefits but also economic and social ones. This objective can be achieved by companies through some changes in their business models, and it could achieve even greater results if it is paired with consumption reduction and more sustainable behaviours undertaken by the population.

Circular Economy is just one of the possible options to address resource scarcity and environmental issues: there are also many other sustainable models which aim to generate a positive impact by leveraging different strategies. For this reason, the first part of this section clarifies the relationship between Circular Economy and sustainability, analysing the main common points and discrepancies, but also the role that the Circular Economy plays in the objective of pursuing sustainable development.

The second part of this section illustrates in detail the definition of Circular Economy, its principles, strategies and the main benefits and drawbacks.

1.2.1 Evolution of sustainability – from Sustainable Development to Circular Economy

The birth and diffusion of the concept of sustainability have seen several historical phases which have led to the creation of different sustainable models, among which the Circular Economy. In 1972, the Limits to Growth report rectified for the first time that the availability of natural resources is limited and the constraint on the planet's ability to absorb pollution places limits on economic growth. After that, the term sustainability was first intended as the processes and actions through which humanity prevents the exhaustion of natural resources, intending to maintain an ecological balance that does not reduce the quality of life of today and future societies (Development's Limit Report, 1972). Starting from this definition, centered above all on the environment and the use of resources, the term has undergone a gradual evolution until it assumed a broader meaning that also included the economy and society. With this intention, the concept of Sustainable Development was introduced for the first time in the Brundtland Report of the World Commission for Environment and Development (1987) as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This definition emphasizes the importance of limitations in order to ensure a sustainable future for the new generations, but without restricting itself purely to the environmental aspect. The first obligations for governments – such as those established during the ONU Rio Conference in 1992 or the Kyoto Protocol in 1997 – were initially centered on facing resource scarcity and the reduction of greenhouse gas emissions. But starting in 2009, a world conference is planned every year to check not only the environmental but also the social and economic progress achieved and re-discussing new objectives.

Sustainable Development, intended as pursuing social and economic progress while respecting the environment, places itself at the center of the three-pillar scheme of sustainability, universally known as the Triple Bottom Line (Elkington J. 1998). This scheme consists of three main areas associated with the three pillars of sustainability - environmental, social and economic – and the intersections between them identify further areas of interest. The socio-environmental area includes for example environmental justice, the socio-economic area involves topics such as labor rights and the economic-environmental area includes issues such as energy efficiency. Sustainable Development can be placed exactly in the intersection of the three areas, whereas Circular Economy, intended as an operationalization for businesses to implement the concept of Sustainable Development (Corona B. 2019, Geissdoerfer M. 2017, A. K. Schröder P. 2019), is more shifted towards the economic-environmental area. Therefore, since circular systems have a minor impact on the social pillar, some authors affirm that a circular system is not necessarily sustainable implying that the main beneficiaries of the Circular Economy practices are the environment and the economic actors, with no or few implicit social advantages (Geng Y. 2012, P. D. Kravchenko M. 2019, Kristensen H.S. 2020, Murray A. 2017). Moreover, it should be taken into consideration that some Circular Economy strategies are not necessarily sustainable even from an environmental and economic point of view. For example, reverse logistics needed to collect used materials to be recycled might increase the carbon footprint of the business, potentially resulting in a greater overall environmental impact (Münch C. 2021). Another example is provided by Agrawal et al. (2012) who underline how product leasing is not necessarily a more sustainable option since on the contrary, it might inspire more frequent product replacement, resulting therefore in a final increase in production. Moreover, using recycled materials could shorten a product's lifetime due to quality loss or require higher use of water and energy. On the other hand, Tukker et al. (2006) demonstrate how result-oriented business models may be more environmentally beneficial than some Circular Economy strategies, leading to the conclusion that not all CE initiatives necessarily have a positive impact on sustainability. For this reason, the authors stress the importance of carefully assessing the potential sustainability performance of any decision about adopting a Circular Economy strategy, before its actual implementation.

Aside from these main conflicts in their focus, Sustainable Development and Circular Economy share several similarities. Among all those identified by Geissdoerfer et al. (2017), it is worth mentioning the interdisciplinary approach, the need for cooperation between stakeholders, the business model innovation as a key to achieving objectives and the importance of regulations and incentives to support the implementation.

To further explore the relationship between Sustainable Development and Circular Economy, it may be useful to also introduce the concept of SDGs. In 2015, more than 150 international leaders from 193 states met at the United Nations to sign the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs) and 169 targets to protect the environment, promote human well-being and contribute to global development through a new strategy. Different authors have analyzed the links between CE and the SDGs (A. K. Schröder P. 2019, Fassio F. 2019, Rodriguez-Anton J.M. 2019). According to them, the Circular Economy contributes directly or indirectly to at least 12 of the 17 SDGs in the UN Agenda 2030 (Table 1). In particular, all the 7 SDGs belonging to the environmental dimension benefit from Circular Economy, as well as for the economic dimension where only 1 out of 5 SDGs is not affected. On the other hand, just 1 of the 5 SDGs in the social dimension is impacted by Circular Economy and this fact underlines again the very minor benefits of a circular approach on this pillar, compared to the economic and environmental ones.

Table 1 SDGs and Circular Economy

Environmental	2. Zero hunger; 6. Clean water and sanitation; 7. Affordable and clean energy; 12. Responsible consumption and production; 13. Climate action; 14. Life below water; 15. Life on land
Economic	1. No poverty; 8. Decent work and economic growth; 9. Industry, innovation and infrastructure; (10. Reduced inequalities); 17. Partnership for the goals
Social	(3. Good health and well-being); (4. Quality education); (5. Gender equality); 11. Sustainable cities and communities; (16. Peace, justice and strong institutions)

In addition to SDGs, other criteria have been promoted to support sustainable development. ESG (Environmental, Social, Governance) refers instead to non-financial criteria that measure the environmental impact of a company, its respect for social values and the quality of management. With respect to the SDGs, the ESG criteria do not consider the economic aspects and therefore do not underline the benefits generated by Circular Economy in this area. On the other hand, this framework allows to highlight the fact that there is no clear relationship between the Circular Economy and the Governance aspect of ESG criteria, except for the business ethics.

In conclusion, from the literature review it emerged that the Circular Economy has a strong and clear impact on the environmental and economic aspects, while instead it has a weaker influence on the social and governance areas.

1.2.2 Main principles, strategies, benefits and drawbacks of Circular Economy

Circular Economy is based on three main principles: design out waste and pollution, keep products and materials in use and regenerate natural systems. In other words, Circular Economy aims to “preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows; optimize resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles; foster system effectiveness by revealing and designing out negative externalities” (Ellen MacArthur Foundation, 2015).

The adoption of these three principles is reflected into the ReSOLVE framework (Table 2), developed by McKinsey (2016), through six different group of actions:

Table 2 - ReSOLVE framework

Regenerate	Shift to renewable energy and materials; reclaim, retain and restore health of ecosystems; return recovered biological resources to the biosphere.
Share	Share assets; reuse / second hand; prolong life through maintenance, design for durability, upgradability, etc.
Optimise	Increase performance / efficiency of products; remove waste in production and supply chain; leverage big data, automation, remote sensing and steering.
Loop	Remanufacture products or components; recycle materials; digest anaerobically; extract biochemicals from organic waste.
Virtualise	Dematerialise directly (e.g., e-books) or indirectly (e.g., online shopping)
Exchange	Replace old with advanced non-renewable materials; apply new technologies; choose new products / services (e.g., green logistics)

Companies can use all these levers, or part of them, to make their business model more circular. Indeed, through the combination of these six main approaches, it is possible to identify several Circular Economy strategies, among which companies can select the most suitable for them according to their needs and objectives, the actors involved and other factors.

In this context, the butterfly diagram by Ellen MacArthur Foundation (2019) represents a useful tool for companies to identify their positioning in the circular system and possible directions for improvement. It is the most diffused graph to visualize the continuous flows of materials, actors and processes of Circular Economy. There are two main types of nutrients, characterized by different cycles: biological and technical, which are described respectively in the left and the right wing of the butterfly model. Biological nutrients are organic materials that come from nature and can be returned via composting or similar processes without negatively affecting the natural environment. Technical nutrients are instead synthetic materials, designed to be reused with minimal energy and the highest quality retention. The cycles in the diagram represent the material flows among different actors and suggest some possible Circular Economy strategies to implement. Typically, the closer the loop is to the centre of the diagram, the more valuable the approach is. Indeed, the outer loops often imply more complex processes, higher costs and greater use of energy and resources to put the materials back into circulation. The butterfly model can therefore help companies to prioritize the highest value opportunities: by designing products to be easily recirculated in the inner loops without working on the materials or creating new business models that facilitate sharing, companies generate the highest possible values for both them and their stakeholders. Moreover, it is preferable to prolong the cycle as long as possible: extending the life of a product allows it to be used and reused multiple times, potentially by many different users. Connecting different circles in an output-input logic between companies or industries allows instead to increase value preservation. In particular, upcycling occurs when the output becomes an input in a higher-valued industry while downcycling is the opposite.

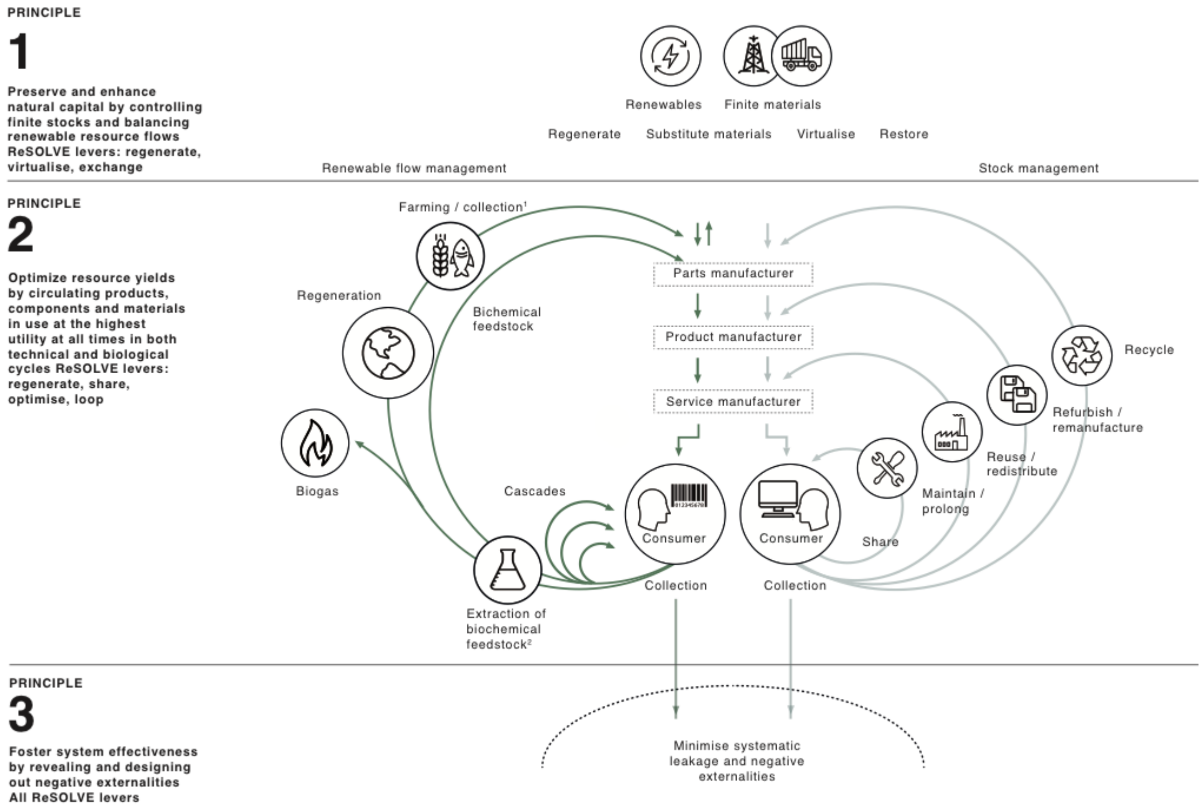


Figure 2 - Butterfly model (Ellen MacArthur Foundation, SUN and McKinsey Centre for Business and Environment)

Figure 2 clarifies which ReSOLVE levers act on each Circular Economy principle and illustrates their connection with the butterfly model.

As said before, the butterfly model proposes some Circular Economy strategies, but it doesn't consider those that are not necessarily related to the flows of materials. Morseletto et al. (2020) propose instead one of the most complete frameworks in literature which lists ten Circular Economy strategies and divides them into three main groups based on their approach, as shown in Table 3. As for the inner loops in the butterfly diagram, also in this case the framework proposes a prioritization for some strategies. When possible, smarter product use and manufacture should be taken into consideration during the design and development phases. The strategies belonging to this group typically occur before all the other strategies, facilitate them and can lead the transition to a Circular Economy before production takes place. The second set of strategies aims instead to prolong the lifespan of products and their parts while maintaining or improving their value. However, these strategies require market receptivity, well-functioning reverse logistics and profitability of the parties involved. For Circular Economy governance, this poses challenges in innovation and requires adjustments to the revenue models and socioeconomic patterns. The last group of strategies aims instead to generate energy and materials from solid waste otherwise unused. Despite the typically low conversion yield rates and very high treatment costs, this set of strategies is where most circular policies are currently concentrated, resulting in relatively little influence on the production and consumption system.

Table 3 - 10R strategies

Smarter product use and manufacture	**R0. Refuse**	Make a product redundant by abandoning its function or by integrating it to a multi-functional product
	R1. Rethink	Make product use more intensive, e.g., through sharing
	R2. Reduce	Increase efficiency in product use or manufacture by consuming fewer natural resources
Extend lifespan of product and its parts	**R3. Reuse**	Re-use by another consumer of a discarded product which is still in good condition and fulfils its original function
	R4. Repair	Repair and maintenance of a defective product so it can be used with its original function
	R5. Refurbish	Restore an old product and bring it up to date
	R6. Remanufacture	Use parts of a discarded product in a new product with the same function
	R7. Repurpose	Use a discarded product or its parts in a new product with a different function
Useful application of materials	**R8. Recycle**	Process materials to obtain the same or lower quality
	R9. Recovery	Incineration of materials with energy recovery

The adoption of these strategies, also called managerial practices, may often encounter some obstacles and barriers. Among them, there are the lack of policies that support the transition to the Circular Economy, the lack of economic feasibility of some circular business models, the low awareness and low willingness to adopt these strategies, the obstacles related to reverse logistics and the lack of proper technologies to implement circular practices. On the other hand, their implementation can generate several benefits including resource optimization, waste reduction, lower CO_2 emissions, a better corporate image and brand positioning on the market, lower production and procurement costs and a higher level of innovation. It is important to underline that these managerial practices contribute not only to reducing the environmental impact but also to making the business models more resilient. Indeed, Circular Economy with its recirculation of resources helps to reduce uncertainty along the supply chain by reducing the exposure to price volatility and supply risk.

1.3 Sustainability Assessment

To ensure that companies' strategies result in true progress towards sustainable production and consumption, companies need to be able to validate and assess their actions. This section provides a presentation of sustainability assessment concept, its characteristics, methodologies, benefits and drawbacks, while the following section presents the evaluation of Circular Economy strategies.

1.3.1 Definition, purposes, benefits and challenges

Sustainability assessment is defined differently in the literature because it comprises several approaches and methodologies used to test, monitor, validate and enhance sustainability actions and efforts inside enterprises and organisations, hence supporting decision-making for sustainable development (Leon Bravo V. 2021).

Sustainability assessment is associated with the broad field of impact assessment, defined as "the process of identifying future consequences of a current proposed action" (Waas T. 2014). Based on this presentation, the most inclusive definition of sustainability assessment can be "any process that directs decision-making towards sustainability".

The definition highlights the main goal of the assessment practises: pursue sustainable development objectives, which can be further clarified by dividing it into four categories (Waas T. 2014):

- Generating information for decision-makers
- Operationalizing sustainable development to foster stakeholders' engagement
- Learning processes and creating new opportunities
- Structuring complex information

The first purpose of sustainability assessment is to support decision-makers by providing them with useful information to aim at sustainable results. By increasing the quantity and quality of information gathered and obtained, the quality of output also improves proportionally. Literature shows that the approach most required by those implementing the decision-making processes is the comparison of alternatives, which therefore requires more elements to analyse (Alejandrino C. 2021).

Information and data are necessary not only for figures internal to the companies but also for an external one. Stakeholders' theory, presented by Leon Bravo et al. (2021), assesses that companies implement sustainability practises mainly to respond to various stakeholders' expectations and pressures. If decision-makers have the capabilities and resources to make decisions, they will also demonstrate sustainable performance objectives required by stakeholders. Their expectations are not only goals to achieve, but they also guide businesses in the decision process to guarantee that economic factors, sustainable operations and processes in all of their dimensions - economic, environmental, and social - are incorporated (Tsolakis N. 2018). Also, Leon Bravo et al. (2021) demonstrate through case study analysis that organisations apply sustainability practices and assessment mechanisms according to the stakeholders they deal with.

The second aim is related to the relation with stakeholders just mentioned. Operationalising sustainable development is required by using measurements and indicators to define specific and explicit meanings. Validating sustainability through transparent and precise techniques is a useful way to demonstrate to stakeholders the commitment and achievements obtained, as well as to assess whether the standards are met. The resulting risk is related to overloading the actors with redundant information and measurements; therefore, their involvement is an essential step for the assessment processes to guide companies to choose the best metrics. Kumar et al. (2021) further add that co-involvement can also benefit in terms of the continuous feedback and fulfilment data requirement, essential for the measurement of values. On the other hand, since each actor at each level has specific requirements to meet, complexity increases due to the different meanings assigned to the measures.

Performing a sustainability assessment means not only measuring, evaluating progress or comparing options (Sala S. 2015), but also promoting and enhancing sustainable choices. The third purpose focuses on continuous and progressive learning, thanks to the knowledge and insights brought by stakeholders and the results of previous assessments. New opportunities are created, and they bring benefits to future analysis.

Last, following standardised methods and procedures allows decision-makers to better manage the multi-dimensional aspects of Sustainable Development and its complexity. Defining clear aspects and principles through indicators is a possible approach for companies to follow.

The literature shows plenty of different methods of sustainability assessments, which differ in scope or range, in support of the various goals that they pursue, as presented above, and the features and aspects of the system under analysis, as single product, process, company or whole supply chain. Regardless of the specific typology of the system, it is essential to consider its dynamic interactions with nature and society around it as trade-offs and/or synergies. Some drivers of sustainability assessment can be identified, they can vary between firms or supply chains. Leon Bravo et al. (2021)

present firm capabilities, stakeholders' importance, and supply chain integration as the most important to consider in the analysis (Leon Bravo V. 2021).

It may be deduced that the possible scenarios assessed when performing a sustainable assessment are complex due to a large number of characterising factors, such as the one mentioned above. Adapting a holistic view can be a solution to overcome this challenge (Iacovidou E. 2017, Stillitano T. 2021). This approach allows managers to capture different benefits and impacts of the elements under consideration, as well as to understand the dynamic interactions of the system analysed with environmental, socio and economic aspects. Only in this way it is possible to achieve effective sustainable assessment. This perspective is even more important when the system under consideration is an integrated supply chain, which is a complicated multi-tier network. It could be made up of several actors, phases, and resources. Assessing the sustainability of a value chain necessitates an examination of each component, as well as their connection, integration, and dynamics. Even the United Nations have stated their vision in this regard, stating that a more holistic approach is needed to achieve sustainable results (UN 2015)

Incorporating sustainable business practises into decision-making processes can be considered the main benefit of measurement and disclosure of sustainable assessment, since it enables businesses to shift their practises away from just environmental management and toward broader sustainable business strategies. Other benefits of reviewing sustainable business practises include stakeholder communication, company benchmarking, and organisational learning (O. K. Roos Lindgreen E. 2022).

Barriers to sustainability assessment have emerged from the articles as well (Alejandrino C. 2021, Mesa Alvarez C. 2021, O. K. Roos Lindgreen E. 2022). The major challenges are related to the complexity of the system originating from data management and system boundaries. Data availability is a relevant phase in most of the methodologies, but companies in some cases are not capable of acquiring and extracting value from them. This deficiency impacts the effectiveness of applying a holistic approach. The latter issue regards the need of identifying demarcation lines in the chosen assessment approach, which can indicate a boundary between what contributes to sustainable development and what does not; and the potential to execute knowledge and solution co-production in a trans-disciplinary setting. Both these issues increase in intensity and relevance as the involvement of stakeholders increases. Lastly, communication and transparency have a critical role in achieving sustainable development.

The identification of limitations enables the development of subsequent capabilities, allowing companies to not only overcome these barriers, but to go further than only compliance. In addition, the revision of assessment approaches themselves can be performed to improve their applicability and relevance.

1.3.2 Methodologies for Sustainability Assessment

This chapter investigates the features of the most common and used methodologies applied for achieving sustainable development. From many approaches, only those frequently cited in the literature have been well presented hereafter.

Firstly, some authors propose a clarification of the different terminology. As Moraga et al. (2019) present, methodology is a set of methods, a method groups different models, tools, and indicators relevant to showing information. More precisely, a model is a mathematical description of calculating an indicator, which can be obtained through a tool.

Among several studies, five general categories are identified and specified as Roos Lindgreen et al. (2022) proposed: lifecycle-based methods, sustainability reporting frameworks, indicators, management tools and optimisation tools.

Lifecycle-based methods are the most applied based on the articles analysed. They enable the quantification of impacts across all phases of a product or system's life cycle. The analysis can be carried out at an economic, social or environmental level, so methods generally used can be LCSA, LCA, Environmental LCC, Social LCA, LCC Capital based, and Environmental Impact Assessment.

Life Cycle Assessment LCA is a structured, comprehensive and internationally standardized method to evaluate the quantitative impact of products, processes, services or systems on the environment throughout their full life cycle. It quantifies all the resources consumed and their relative impact on the environment, human health and other resources and subsequently classified them into impact categories, so environmental dimensions of the value measured using indicators: global warming, stratospheric ozone depletion, acidification, terrestrial eutrophication, aquatic eutrophication, photochemical ozone formation, human toxicity, ecotoxicity and resource depletion (Iacovidou E. 2017). These categories are used as drivers to evaluate sustainability in relative terms: it is more complex to analyse it from an absolute perspective because different elements of a system can led to different recommendations. So, using LCA is particularly useful in comparing alternate strategies, because it allows one to understand the trade-off between the benefits and impact of different systems (K. M. Saidani M. 2021), or coupled with input-output analysis to achieve a comprehensive analysis (Walker A.M. 2021).

If the evaluation object of the method is no longer the environmental aspect but the economic or social ones, this would result in the Life Cycle Costing LCC and social Life Cycle Assessment sLCA models respectively. They adopt a similar approach as LCA, following the same procedure, except for a specific sLCA model –UNEP/SETAC approach – which includes 3 further steps. The difference between LCC and sLCA regards the focus: the former assesses the economic impact of a product, process, service or system based on conventional, environmental or societal perspective. It enables comparative cost assessments to be made over a specified period, summarizing all relevant economic factors both in terms of initial costs and future operational costs associated with the life cycle of a product. On the other hand, sLCA identifies significant social phenomena relevant to assessing the positive and negative social consequences of a material, component, or process during its lifecycles, such as human rights, working conditions, and health and safety, on stakeholders (Iacovidou E. 2017)

Both LCC and sLCA include also impact categories and indicators. The former has costs as key impact categories, while there are fewer categories relating to prices, revenues, NPV, or contribution to GDP (Alejandrino C. 2021). The impact categories for sLCA are classified by stakeholders, which are the core of the analysis. Moreover, they can differ based on the guidelines adopted, UNEP/SETAC guidelines or the PSIA. Scoring systems, indicator selection and weighting methods are proposed as methods to assess the impact categories, they are the methodologies most implemented based on literature (76% UNEP, 16% none, 4% PSAI, 4% other methodologies) (Mesa Alvarez C. 2021).

Stakeholders play a key role also in LCC assessment: the results strongly depend on the actors' perspective that is considered. Environmental LCC is a variant of the methodology, it includes the costs incurred not only by the companies but also by all the affected stakeholders (Niero M. 2017).

The main challenge related to the sLCA approach concerns data. Primary data collection is limited at the appropriate level of detail, numerous assumptions must be made, resulting in conclusions that are not very precise (Mesa Alvarez C. 2021). The process is more heterogeneous, mixing measurements and qualitative questionnaires or interviews with stakeholders. On the other hand, direct measurements are typically used to acquire primary data in LCA and LCC (Sala S. 2015). For what concerns secondary data, they primarily derive from public/commercial databases. In other circumstances, information is gathered from the literature (similar case studies) or business reports. Secondary sources are employed equally in LCA (both close to 50%), however, literature data is largely used in LCC and sLCA. Only 20% of the case studies examined for these two pillars utilised databases. The fact that social and economic commercial databases are still in their infancy may explain the limited usage of databases in LCC and sLCA. (Alejandrino C. 2021). Furthermore, the outcomes of the analysis are primarily qualitative and semi-quantitative.

Combination of the three aforementioned techniques would result in Life Cycle Sustainability Assessment LCSA framework. This methodology analyses the system based on all three pillars of sustainability (economic, environmental and social aspects) and in its full life cycle (Niero M. 2017). It aims at obtaining a holistic perspective of sustainability, but the alignment of the typologies of results coming from the three methods increases complexity, so few businesses apply it and prefer to treat each pillar independently (Mesa Alvarez C. 2021). Methodologies presented later as “optimisation tools” are increasingly being applied to face this issue since they consider in the analysis more attributes and variables (Alejandrino C. 2021).

A variation of LCSA is the capital based LCSA framework. which evaluates sustainability by examining the stocks and flows of eight different types of capital, or resources creating values: natural, human, financial, manufactured, social, cultural, digital and political. LCA, LCC and sLCA results are used to evaluate the flow of these capital stocks in terms of maintenance or conservation of capitals. This approach allows for the evaluation of how capital flows in a product's life cycle contribute negatively or positively to depleting or renewing capital stocks. Based on stock availability and transformation, this technique can assist companies in deciding about a product or organisational life cycle possibilities (Subramanian K. 2021). Evaluating the maintenance of capital stocks is conceptually considerably closer to the Brundtland definition of sustainability than the TBL-based LCSA method. The impact categories in the current LCA methodology adequately encompass the degree to which product or process life cycle impacts the natural capital. Indicators from the sLCA and LCC approaches primarily cover other capitals like human, social, and financial. Most crucially, albeit the level of methodological maturity varies, LCA, SLCA, and LCC are easier to use compared to LCSA because they are already very well established independently. The problem that emerges concerns the complexity of unified outputs.

Most life cycle frameworks are structured in four phases, which are interconnected and performed in an iterative process (Alejandrino C. 2021).

The scope and goal definition phase includes the definition of system boundaries, also in terms of stakeholders’ involvement. Boundaries are usually classified according to the life cycle stages including in the analysis: "cradle-to-grave" systems encompass all stages of the system's life cycle; "cradle-to-gate" systems exclude the stages of usage and end-of-life from the analysis' boundaries; and "gate-to-grave" systems exclude raw materials acquisition and inputs manufacturing. Other approaches, such as "gate-to-gate," only evaluate operations within facility gates, whereas "end-of-life" only considers management activities related to final disposal, recycling, refurbishment, or energetic valorisation.

In the Life Cycle Inventory phase, data regarding the possible input and output that may cause an impact are collected and classified.

Life cycle Impact Assessment phase performs the analysis of environmental impacts. This phase provides additional information in the assessment of the Life Cycle Inventory.

The Life Cycle Interpretation phase aims to summerize and discuss the results of phases 2 and 3.

A more complex approach compared to LCA in terms of system boundaries and the functional complexity of processes is Material Flow Analysis MFA. MFA-based methods are a precursor to LC methods, and they establish an overview of resource and energy flows across the life cycle of a system (O. K. Roos Lindgreen E. 2022). It is frequently used since it focuses specifically on the analysis of flows into and out of a system. This tool identifies the most critical fluxes (inputs and outputs) in terms of quality and quantity, as well as detects the system's environmental consequences. If one wanted to focus on the analysis of economic resources, input-output model allows the analysis of the relative relationship between the flow of production inputs and the subsequent flow of produced outputs in an economy. This linear modelling approach replicates the immediate and delayed effects of changes in output levels on economic indices like national output, employment, gross value added, and the trade balance (Jacob C. 2021). In a similar but more thorough way, MFA is effective for modelling, interpreting, and optimising "socio-metabolic systems," which refer to the dynamic but unstable equilibrium of the articulated system consisting of nature and society (Amicarelli V. 2021). Saidani et al. (2021) also argue that both LCA and MFA have their limitations when it comes to assessing the effects of a prototype product. They are based on already-produced items and allow for a solid evaluation of past performance, but they make it more challenging for engineers to decide on things that are still being built.

Footprints tools and accounting methods take on a similar approach (carbon, ecological, product environmental, water).

The Emergy Accounting method EMA is a method based on thermodynamic theory, which tracks the energy conversion path of products to assess the ecological impacts. It converts the different kinds of resource into a unique value, emergy, defined as “the available energy of one kind (usually solar) directly or indirectly used in a system for transformations leading to a product or a service” (Santagata R. 2020). In this way, EMA could integrate spatial and temporal factors and allow comparison and analysis.

It is appropriate for studying complex ecosystems generated by human economic activity and natural environment evolution in combination. In terms of evaluation methodologies and research areas, Wang et al. (2020) argue that EMA and LCA are similar in the target system's upstream (mostly in the creation of inventory databases), however, the downstream environmental impact assessment techniques are dissimilar, since they respective emphases are on different aspects of macrocosms and microcosms. Both EMA and LCA prioritise the assessment of system sustainability, through the determination of system boundary, data list analysis, model computation, and result interpretation, although the former has distinct advantages in analysing natural system inputs while the latter is more persuasive to system resource usage and environmental effect due to its flexible and comprehensive framework. In other terms, EMA has a donor-side perspective, while LCA is a user-side evaluation method. Coupling these theories allows to benefit from both: the LCA framework can help compensate for the EMA procedure's limitations in impact analysis and the standardisation of energy flow distribution. With resource-specific treatment choices and a quantitative study of ecosystem services, EMA can be used to complement LCA (Wang Q. 2020)

The assessments mentioned above show a gap that emerged repetitively from the articles' analysis: it regards the lack of standardized methods and accounting for all domains of value, especially for the social one (P. D. Kravchenko M. 2021). The goal of sustainability reporting framework is to fill this deficit creating a common language and format for organisations to report their sustainability impacts. Two methods mentioned in the literature are Global Reporting Initiatives GRI standards and Environmental Accounting (O. K. Roos Lindgreen E. 2022).

GRI deserves a further explanation: it provides environmental, social and governance (ESG) standards to reflect global best practices for sustainability reporting. These guidelines help every type of organization to assess economic, environmental and social impacts comparably and transparently and contribute to Sustainable Development. Moreover, companies can respond to information demands from stakeholders and regulators, such as investors, politicians, capital markets, and civil society, in addition to reporting corporations (GRI s.d.).

Another tool to help standardize is the indicators approach. The indicators category is one of the most important and well-known among sustainability assessment methodologies since they can support the assessment both in the early stages of any business process to provide visibility about the potential implications of the designed solution, and in the last phase to evaluate the implemented process.

An indicator can be defined as a measurement (qualitative or quantitative) expressed by a variable (parameter) or a function of variables, that can indicate the state or level of a target (Hallstedt S.I. 2017, Moraga G. 2019). An indicator is different from a variable because the former is related to a reference value, while the latter does not give information about changes in the status of a system and does not point towards anything (a goal, an aim, a standard, a benchmark, etc.). As a result, it does not gain meaning (Waas T. 2014). Vinante et al. (2021) also show differences between indicators and metrics terminology, by defining the latter as measurable quantities for tracking an indicator, where the indicator normally has a broader focus. Waas et al. (2014) adopt an opposite perspective, arguing that indicators are frequently simplified and combined into a single statistic known as index. Corona et al. (2019) instead provide a further clarification between indices and indicators, comprising them in what academics refer to as 'metrics': the former aims at providing a value expressing the intrinsically sustainable degree of a system, while indicators are scores aimed at analysing the contribution of strategies to the achievement of principles.

Their main strength of indicator is the capability to represent a clear goal to achieve, structuring information in a meaningful way to create knowledge. It aims at tracking, monitoring and measuring the progress and performance of a particular product, process or system, comparing and measuring a relative difference between solutions (De Oliveira C.T. 2021). Leading indicators can generate simplified measures and results of TBL performances that can help drive actions to improve a product's sustainable performance (K. M. Saidani M. 2021). Saidani et al. (2021) also state that indicators are more helpful in identifying potential changes that could be made to the products to make them more environmentally friendly, while methodologies mentioned before, such as LCA allow to assess the present impact for different items.

Many different indicators exist. Literature presents two sides. On one hand, there are different databases containing specific and detailed lists of indicators. An example is provided by the Technical University of Denmark DTU, which grouped into a single database 271 leading sustainable indicators, classified by dimensions of TBL (P. D. Kravchenko M. 2019). On the other hand, some authors over-aggregate the values, hiding relevant information and focusing directly on what they are interested in, creating a wide and uncertain picture of the system they are working in (Calzolari T. 2022).

While lifecycle-based approaches emphasise analysis from a life cycle perspective, assessment methods such as Strategic Environmental Assessment, Environmental Risk Assessment, Sustainability Balanced Scorecards, and Cost Benefit analysis allow for the evaluation of performances and their management. The last two methods mentioned are those explored in depth in the literature and therefore presented below.

Balanced Scorecards BSC approach develops strategic objectives that can be used to benchmark performance indicators and allocate desired results. This tool can be applied from a sustainable perspective, having economic, environmental or social aspects as goal of the analysis. Sustainable Balanced Scorecard SBSC concept is categorized as an assessment method since it provides communication, connection between strategic objectives and measures in the form of planning, targeting and aligning strategic initiatives, and improvement of strategic learning feedback, which are the purposes of SA presented above (Trisyulianti E. 2022).

Since economic implication is a relevant area to evaluate alongside environmental, social, and technological elements to sustain the overall viability of any proposed decisions, Cost-Benefit Analysis CBA converts all costs and advantages to monetary terms providing a transparent, clear, and systematic assessment, and steps to increase the economic viability of the processes, such as technical innovations and improvements, can be implemented. According to critics, this method can also produce misleading comparability due to methodological bias toward recognising just what can be monetised and emphasising the incompatibility of CBA with sustainability (Iacovidou E. 2017).

All these evaluation methodologies lack an integrated vision to consider more attributes and variables inside the analysis and obtain a final output which reflects more consistently the system (Alejandrino C. 2021). Decision-support methodologies based on mathematical programming, simulation, multi-criteria decision-making can be integrated to face this challenge. It should be noted that the lines between the evaluation and decision-making phases are sometimes blurred and overlapping (Iacovidou E. 2017). Such optimisation approaches capture and integrate different aspects obtained from each sustainability pillar and aim at obtaining a holistic perspective. These tools are suitable for complex problems featuring high uncertainty, conflicting objectives, multiple interests and perspectives (Holog A. 2011).

In particular, multi-objective decision-making MODM methods are used to identify pareto optimal solutions, while multi-criteria decision-making MCDM methods are used to evaluate and boost a set of alternatives based on multiple attributes (Alejandrino C. 2021).

The MCDM most used is Analytic Hierarchy Process AHP. It is a mathematically based process which considers different stakeholders' perspectives and sustainable criteria, to obtain a clear, aggregated framework to assess decisions (Alejandrino C. 2021). This method consists of three steps: structuring a complex problem as a hierarchy of objectives, criteria and alternatives; comparing elements in each hierarchical level by pairs to each element of the previous level, and vertically synthesizing judgements about the different hierarchical levels. The AHP is particularly effective for those cases when there are multiple options and when the criteria have different units or scales (García-Bustamante C.A. 2018), so, it can support LCSA in providing homogeneous output to compare.

Even these last tools are not able to fully capture the complexity required when a sustainability assessment is needed. They should be improved to adopt a comprehensive analytical approach and consider all various differential aspects, from environmental, to economic, social and technical. A transdisciplinary approach helps to overcome this issue, integrating different methodologies and exploiting their advantages. In this way, it is also possible to consider aspects more relevant for stakeholders and local authorities. It is essential to pursue this goal because sustainability assessments can be powerful decision supporting tools that foster sustainable development (Leon Bravo V. 2021). Their effectiveness is improved when a holistic approach is adopted and stakeholders' involvement, temporal and spatial boundaries, and rebound effects are included in the analysis (Kumar M. 2021, Mesa Alvarez C. 2021, Sala S. 2015).

1.4 Circularity Assessment

One of the most powerful and effective ways for companies to contribute and accomplish sustainability development objectives is by implementing CE strategies (P. D. Kravchenko M. 2021). According to what was presented in section 1.2, frameworks and models applied as the 10 R-hierarchy or butterfly model, determine different strategies. It is essential to quantify their impacts, validate their contributions, and document efforts and performances achieved (Sassanelli C. 2019). Therefore, a CE assessment is required.

1.4.1 Definition, purposes, benefits and drawbacks

No explicit and precise definition of CE assessment has been found in the literature, but it can be deduced from the purposes assigned to it. Different authors indicate several specific goals that the assessment should aim at.
First, the purpose of performing an assessment is to obtain a measure of the extent that the CE principles are followed (Corona B. 2019). The results obtained from the analysis need to be meaningful to be drivers for determining subsequent circular strategies to apply, so decision-makers can exploit assessment methodologies to acquire more information from the outputs (Blomsma F. 2017). Another purpose of methodologies is to interrogate the systems and their multi-aspect and contexts to learn more about them from a CE perspective (Ghisellini P. 2016).
Moreover, the methodologies have a structural base which is essential for the alignment of stakeholders in the activities pursued and results achieved. Their effectiveness is increased when they are able to operationalize accomplishment and information (Helander H. 2019). Other studies highlight that using indicators eases the communication of information also to consumers (S. R. Roos Lindgreen E. 2020).

The benefits emerging from the literature can be categorised into two domains: external communication and collaboration, internal improvements and insights. Assessing CE performances enhances the relationship with stakeholders and other external actors, as clients, because it demonstrates the value of having implemented CE strategies. Internally, assessment benefits companies because it provides a learning experience, and not only receiving results (O. K. Roos Lindgreen E. 2022).

Even if the CE assessment concept is presented in a good number of articles, the maturity level is low. The topic is in an early phase, constantly being developed and expanded, it doesn’t present a unified vision at literature level, and it generates ambiguity and uncertainty. Challenges are related to intrinsic aspects, such as the meaning of the assessment or the lack of assessment tools, and to practical ones, so more related to effective measurement and applications (Calzolari T. 2022, Sassanelli C. 2019).

For some authors, the distinction between sustainability assessment and circularity assessment is clear. Circularity assessment has a narrower scope compared to sustainability one, focusing on material use and resource management. Instead, others consider both assessments the same, thinking about CE as a recent version of sustainability, with the existing sustainability assessment tools applicable to CE as well. This issue stems from a lack of consensus on definitions and underlying concepts. The consequence is that present evaluation methods are used for both sustainability and/or circularity at the discretion of individual companies, Roos Lindgreen et al. (2022) performs an analysis on 97 companies and 22 methodologies, and the results show that on average, 53% of organisations adopt one of these methodologies both for sustainability and circularity assessments, 18% only for sustainability, 12% only for circularity, while 17% are not known familiar to the approach considered. In general, few authors present applications in case studies or empirical evidence (Alejandrino C. 2021, O. K. Roos Lindgreen E. 2022).

Roos Lindgreen et al. (2022) and Padilla- Rivera et al. (2021) have also identified several barriers concerning the effective measurements of CE performances. These limits regard company size, which limited the availability of data and resources, such as time, financial assets, employee skills and competencies; or system complexity, as the difficulties in benchmarking the results, considering all CE aspects or principles or involving stakeholders.

Therefore, clarification and specific methodologies are needed, in order to show the connection between the sustainable dimension and specific CE strategies.

1.4.2 Methodologies

As a result of the schools of thought outlined above regarding how circularity and sustainability assessments can be perceived, the methodologies found in the articles can be categorized into two groups. The first typology includes sustainability assessments which are used also for assessing CE practises. The other one consists of a set of specific methodologies applicable only for validating CE principles.

Different authors review sustainability assessment methodologies as possible tools for circularity assessment. Lifecycle-based methodologies (i.e., LCA, LCSA, MFA, EMA) are the most applied since they focus on examining the whole system variables during the lifecycle (Vinante C. 2021). Moreover, MCDM assessments are a suitable methodology since they analyse all the possible variables involved in the system, along almost the entire lifecycle. LCA approaches can help CE in a variety of situations since they consider one or more of the CE dimensions studied due to the wide range of indicators accessible (Elia V. 2017). MCDM assessments are also suitable methodology since they analyse all the possible variables involved in the system, along almost the entire lifecycle. In order to consider correctly the dimensions in the analysis, the combination or expansion of these existing and conventional frameworks is required, such as the improvement of LCA suggested by Zhang X. et al. (2013) of adding circular model analysis at the first step in order to enable the objectives of circularity to be achieved more precisely, or complementation of CE indicators to increase the level of precision. Since the circularity perspective has to deal with all three sustainability pillars, LCSA appears to be the most comprehensive methodology (Niero M. 2017). Instead, Elia et al. (2017) suggest concentrating on the measurement and analysis of natural resource input, recyclable material use, and their flows applying MFA. This tool better highlights material loss and, more in general, its inefficiency, consumption, and waste, targeting the aim of CE principles. Kravchenko et al. (2019) support this idea as well, showing that it is applied especially from a macro perspective to identify where CE activities can be implemented and substitute linear ones. The limitation of this tool is the lack of quantification of environmental damage and its inability to measure other impact categories, such as emission reduction (Elia V. 2017). What the MFA method fails to capture can be found by the implementation of the EMA: it focuses on circularity approaches to energetic flows, performing analysis of energy use from both fossil and renewable sources, providing information not only on energy quantity but also on energy quality (Elia V. 2017), but, similarly to MFA, it lacks contribution to the assessment of other dimensions. The integration of the two methods among them or with other indicators allows these gaps and limitations to be bridged. Amicarelli et al. (2021) present a series of material cycles and eco-efficiency indicators developed from the combined effect of material flow results and socio-economics indices, obtained through MFA. These indicators allow to retrain the use of natural resources by tracking the flow of all resources from the natural world to society (and vice versa), and they also capture the ecological efficiency of growth by measuring how effectively economic activity affects both consumption and production levels as well as the corresponding environmental effects.

Concurrently with the evaluation, performance management is necessary. Sustainable balanced scorecards SBSC has been integrated with circular strategic choices resulting in a framework useful in company’s performance management systems. The model finds necessary to consider stakeholder values to formulate organisational strategic goals (Trisyulianti E. 2022). The proposed model pursues reduce, reuse, recycling, remanufacturing, and disposal of circular economy performances.

The single methodologies just presented can be suitable for assessing circularity, as supported by Niero and Hauschild (2017) and demonstrated also by Iacovidou et al. (2017), but a combination of assessment methods is required for sustainable management to cover different domains of value and obtain a holistic vision, which accounts for the complex value of the systems. The applicability of previously mentioned methodologies requires huge input information and knowledge. Moreover, the results of these assessments are complex and may not be easily understood in strategic and tactical decisions concerning circularity (P. D. Kravchenko M. 2021). A combination of them should also be required to help companies, but the tools obtained would no longer be simple, straightforward, and practicable, conditions that would be necessary to fulfil in order to evaluate the system under observation in the best possible way.

Indicators can be a possible response to this issue, enclosing multiple dimensions of value in a single element. They provide a better insight into the strengths and weaknesses of the circular solution, thus enabling more informed and balanced decision-making for sustainability (De Oliveira C.T. 2021).

Several circularity indicators have been developed and analysed, based on a wide range of perspectives, formats, and scales. The number has significantly increased in the past few years. Saidani et al. (2019) propose a taxonomy of 55 indicators, some of them also included in the 63 metrics analysed by Parchomenko et al. (2019), De Oliveira et al. (2021) present a critical analysis of 58 indicators. Sometimes indicators are presented with different nuances, hinting at one aspect more than another, and classified according to principles and criteria that vary even slightly from author to author.

Overall, some trends can be identified among all the articles considered. First, even if CE is presented to support sustainable development, results show an unbalanced inclusion of the three dimensions, illustrating that the majority of indicators are environmentally based and so focus on material and resource recovery strategies, while the second most frequent relies also on economic aspects, limiting the inclusion of social aspects. It consequently appears that the link between CE and sustainable development is underdeveloped and needs to be further defined.

Another characteristic that emerged most from the literature study concerns the level of analysis of the indicators. International organizations and entities present some indices which mark the global trend of circular trends, European Commission promotes ten indicators related to four macro areas (production and consumption, waste management, secondary raw materials, competitiveness, and innovation) to capture and monitor the progress towards CE (Eurostat s.d.). These typologies of indicators aren’t suitable for companies to assess and control their operational businesses and activities oriented to circularity, but they are more useful at a regional, national, or international level to represent the key components of a circular economy.

The other macro indicators present in the literature are the aggregation of several sub-indicators. The combination criterion may be by similarity, i.e., an indicator is promoted at the meso or macro level that focuses on energy use and includes other specific and clear sub-indicators on a particular energy-related aspect; or to achieve an integrated view that considers heterogeneous aspects (P. D. Kravchenko M. 2019). Companies and businesses must acquire a huge quantity and precise data, spending resources (economic, time, ...) in order to achieve a single result, which is often hard to interpret. So, aggregating different values increase complexity in the calculation, while using simpler and more practical indicators can allow to obtain direct impact in the results and more efficient analysis.

Micro indicators are suitable for this goal, assessing specific aspects of a product and analysing its contribution to circularity. On one hand, the increasing presence of a wide number leads to utility allowing more and more aspects to be covered, but it generates also a lack of detail and clarity, inconsistency in terms of their scope, purposes and potential applications, resulting in overabundance and confusion (Corona B. 2019, Y. B. Saidani M. 2019). Literature highlights the need for clarification of these indicators to improve their effective usage and implementation. Furthermore, there is no common circularity approach to follow, neither in terms of which CE principles include nor the method used (Kristensen H.S. 2020). Several online tools have been found to assess the level of circularity. Circularity Check, provided by Ecopreneur, determines a circularity score for a specific product or along the entire operations of a company. Going beyond the simple assessment of circularity, Evans et al. (2013), Bovea et al. (2018) and Ellen MacArthur Foundation promote possible tools which can identify any potential developments and opportunities in circularity, called respectively Circular Economy Toolkit, Circular Design Criteria and Circulytics. Similar to the previously mentioned framework, they are structured in a defined number of questions that businesses have to answer. The responses act as drivers and guidelines to define circularity improvements based on categories. The first tool has seven clusters related to the R strategies (repair, reuse, remanufacture, recycle), CE production, use, and business models (Evans J. 2013), while the latter is based on CE concepts of product life extension, disassembly, product reuse, component reuse, and material (Bovea M.D. 2018).

Some circularity metrics focus only on determining to what extent material cycles are closed and do not represent the systemic and multidisciplinary nature of the CE (Corona B. 2019) or the sustainability performance of circular systems (De Oliveira C.T.

2021). The majority of circularity measurements fail to concurrently consider how long a resource is actually being used while attempting to quantify the circularity of resource flows (Rocchi L. 2021). Instead, Figge et al. (2018) propose the Combination Matrix in order to combine the longevity and circularity perspectives based on the assumption that the results obtained from the independent application of these two metrics can lead to distinct results. The created strategies allow companies to take into consideration the benefits that emerged from the remanufactured product along with the recycling aspect (Figge F. 2018). The adherence of supply chains to the CE paradigm is still lacking, even if it is essential in some life cycle analysis (Calzolari T. 2022).

Kravchenko et al. (2019) suggest that a database of performance indicators is a first building block of a foundation for the development of a sustainability screening framework, which will also comprise a procedure for a systematic indicator selection and guidelines for decision-making for sustainability in a CE context

Other frameworks are created specifically for the CE assessment, and they are not valid for sustainability purposes, as Cradle to Cradle (C2C) design framework. It is presented by Niero and Hauschild (2017) and aims at enhancing the positive impact of products through the design of "eco-effective" solutions. It addresses the environmental and social aspects focusing on the CE principles of keeping materials in use and regenerating natural systems. Its vision is founded on three principles: everything can be a resource for something else, energy should be renewable, and no "one-size-fits-all" solution exists. The value added by this framework regards the distinction between two material cycles: the technical and the biological ones. Another benefit concert the C2C certified product standard, which is one operational instrument that enterprises can use to implement the C2C vision following determined steps, present also as “C2C certification program”.

It is important to emphasise again how the relationship between sustainability and circularity is critical in some respects because sometimes the application of the two approaches can lead to inconsistent results. Numerous indicators, based on strategies from the R-hierarchy model, are unsuitable to assess also the TBL dimensions (Corona B. 2019, O. K. Roos Lindgreen E. 2022). Frameworks were presented to be able to use sustainability indicators in a circular perspective without achieving conflicting results, as the trade-off navigation framework presented by Kravchenko et al. (2021), who identified criteria and a structured approach to frame a decision in an uncertain context.

Overall, frameworks are necessary to support researchers and decision-makers in evaluating methods to be applied for measuring quantitatively the effectiveness of CE strategies (Elia V. 2017).

1.5 Classification

Several classifications of frameworks and indicators emerged from the literature review. In most cases, the aim is to clarify circular economy topic still characterized by great variety and confusion, supporting evaluators and decision makers in choosing the methodologies that best suit their needs. This section therefore describes the main and most recurrent classifications, highlighting the characteristics of each category of frameworks and indicators, together with the main advantages and disadvantages of adopting a certain type rather than another.

Nano, micro, meso, macro

A first classification of indicators mentioned in several articles is the one addressing different scales, in particular micro, meso and macro level (Ghisellini P. 2016, Kirchherr J. 2017). De Oliveira et al. (2021) suggest an even more specific categorization including also the nano level. According to this last classification, nano indicators refer to single products or materials, micro level to the whole companies, the meso approach applies to a supply chain perspective and finally macro level refers to Circular Economy development in cities and regions, often promoted by governments and involving the redesign of infrastructural systems. The purpose of introducing the nano level should be to overcome the fact that micro level indicators may not always cover the complexity of a Circular Economy. As pointed out by Roos Lindgreen et al. (2020), grouping all products and materials under the same category to assess company level circularity may be overly general and therefore the further division into the nano level may help to dissolve the confusion derived from a far too broad view. Moreover, De Oliveira et al. (2021) underline how the difference between micro and nano level lies mainly in the scope investigated. While nano metrics deliver results aimed at improving product quality and resource recovery, micro indicators are more focused on value generation through proactive waste management strategies. However, the fact that nano level indicators focus on specific products and materials does not exclude that they might suggest possible strategies to improve the overall company circularity. Moraga et al. (2019) instead focus more on the confusion generated around the macro scale, which is usually limited to the city, regional or eventually national level although some authors suggest going beyond single countries by adopting a more global scale (Kirchherr J. 2017).

Although this classification among different CE scales is neither consistently used nor clearly defined among different authors, it underlines the importance of considering in the performance assessment also what goes beyond the company boundaries, since the Circular Economy often involves different actors of the supply chain and other stakeholders in its implementation (Calzolari T. 2022).

Ex ante, ex post (leading, lagging)

Many articles have focused on the comparison between leading and lagging indicators, highlighting the pros and cons of carrying out an ex-ante assessment instead of an ex-post one. Lagging indicators are often referred to as reactive indicators, since they are used to measure the past performance of the initiatives already implemented by the company. For this reason, they represent a very useful tool for identifying corrective actions but as pointed out by Pojasek et al. (2009), they may not offer useful information about the exact causes of past performance. On the other hand, leading indicators apply a more proactive approach, giving advance guidance and warning about proposed actions. In this way, they give companies the opportunity to adjust and improve the solutions even before the implementation, by supporting decision-makers in the identification of the relationship between the decision to be taken and the potential impact on performance (Epstein M.J. 2001). Of course, the uncertainty of data in the early stages may be greater than in the ex-post evaluation and indeed lagging indicators are the preferred ones for corporate reporting, since they provide more precise information about performance achieved. However, leading indicators are more useful for structuring information in a meaningful way, which leads to knowledge creation about a certain context, thus facilitating decision-making and process management.

Environmental, social, economic / governance

Almost all the companies analyzed in literature classify their indicators according to the Triple Bottom Line, based on the concept of Sustainable Development. Indeed, Circular Economy is widely intended as an operationalization for businesses to implement the concept of Sustainable Development (Corona B. 2019, Geissdoerfer M. 2017, A. K. Schröder P. 2019) and therefore companies "develop and implement CE practices that focus on gaining and maintaining economic advantages while minimizing environmental burden and maximizing social prosperity" (P. D. Kravchenko M. 2019). Consequently, sustainability and Circular Economy performance indicators can be applied to evaluate how the implemented strategies help businesses to advance in the TBL domains.

Indicators belonging to the environmental dimension concerns the identification and management of organization's impacts on the natural ecosystems (Bell S. 2008, Sauve S. 2016). They typically capture aspects included in environmental sustainability reporting and related to resource consumption (material, energy, water, land), use of chemical and harmful substances, waste generation and emissions to water, soil and air (Joung C.B. 2013).

Economic indicators aim instead to measure the value creation of a company, supported by long-term relationships with customers, partners and suppliers (Elkington J. 1998). Costs, revenues, investments, knowledge management, and innovation are some of the elements included in the economic component that are widely employed in corporate reporting (P. D. Kravchenko M. 2019).

Finally, social indicators are defined by the UN as those "that address identification, accounting and management of values and needs of different stakeholders of a company", where the stakeholders can be identified as "internal and external groups of people that interact with and directly or indirectly affected by the company and its activities" (Labuschagne C. 2005). Therefore employees, customers, suppliers and local communities are the typically considered stakeholders, while the most common aspects addressed by the indicators are employment conditions, training and education, health and safety of customers and employees, human rights, equality and stakeholder relationships (P. D. Kravchenko M. 2019).

Several authors classify the indicators taking into account also the governance aspect coherently with the ESG criteria, considering as governance indicators all those that refer to management and decision-making. (P. D. Kravchenko M. 2019), for example, introduces the concept of extended TBL, distinguishing between purely economic and governance metrics. On the one hand, economic indicators are the most suitable to highlight the competitive advantage and the monetary results achievable through the adoption of CE practice. But on the other hand, the authors underline the role of governance indicators in evaluating the strategic approach to Circular Economy implementation and the importance of including them in the overall assessment.

Although various international directives and most authors stress the importance of considering all three pillars of TBL equally important when making decisions and measuring performance in the sustainability context (Badurdeen F. 2015, Joung C.B. 2013), the literature highlights a strong prevalence of environmental indicators over economic and social ones (Ahi P. 2015, Joung C.B. 2013). This is not surprising, considering the widespread ambiguity of the term sustainability which is often reduced to environmental considerations. However, economic indicators still represent 25% of all metrics found in literature (P. D. Kravchenko M. 2019), coherently with the fact that environmental and economic objectives are core concepts of Circular Economy (Sauve S. 2016).

The strong underdevelopment of social aspects related to CE is highlighted by almost all authors in literature, among others Geissdoerfer et al. (2017), Geng et al. (2012), Kravchenko et al. (2019), Kristensen and Mosgaard (2020), Murray et al. (2017). However, a debate has arisen about whether social aspects should be included in CE assessment (L. A. Schröder P. 2020), or if this inclusion would result in a mere reinterpretation of sustainability-related frameworks (Geissdoerfer M. 2017). Indeed, currently available social CE metrics clearly focus on internal social aspects, such as those referring to employees, probably due to the fact that they are more quantifiable (Fan C. 2010, Feil A.A. 2015). Conversely, the social context outside organizations' boundaries including suppliers, customers and the local community, is not enough represented by the identified metrics and this can be due to a qualitative nature of external aspects which is often difficult to measure objectively. But considering the importance of external stakeholders in the Circular Economy context, it may be necessary to include external view metrics within CE assessment rather than the internal ones (Kirchherr J. 2017, Moreau V. 2017). In other words, if social aspects are to be considered, additional CE metrics should be developed considering the social context outside organizations' boundaries; otherwise, the present indicators focused on more internal aspects should be discarded in assessment practices, as they are not comprehensive for the purpose of CE evaluation (Vinante C. 2021).

CE strategies

Many articles in the literature have classified the indicators according to the different Circular Economy strategies that they impact. In this way, it is possible not only to understand what the advantages and disadvantages are of adopting a specific strategy compared to a linear economy model, but also to compare different Circular Economy strategies with each other in order to understand which would be the best to implement. The number and type of Circular Economy strategies considered for this classification varies between the different articles, based on the theoretical model of Circular Economy to which they refer and possibly also to the specific sector under consideration. Kravchenko et al. (2019) is the one that adopts the broadest view, classifying the indicators among 13 different Circular Economy strategies in line with the framework proposed by Potting et al. (2017). The classification was done based on the correlation between the activities implied by a strategy and the focus of indicators measurement. Their analysis found that the Circular Economy strategy most covered by performance indicators is *Reduce, restore and avoid impacts in manufacturing*, with 70% of the indicators referring to the environmental pillar. The strong prevalence of environmental indicators reflects the same dominance found in the literature, but it is interesting to note how this strategy and others involved with the reworking of raw materials show a significant coverage by social indicators. This is probably because these strategies often involve labor-intensive activities, and indeed many of their social indicators refer to employee-related aspects. On the other hand, it's worth noticing that strategies focused on product use are scarce on the assessment of the social pillar, despite the importance of the users' role for the success of many Circular Economy strategies implementation. The fact that the strategy with fewer indicators is *Reinvent the paradigm* underlines instead the difficulty in evaluating the Circular Economy strategies most linked to the design and planning phase. All these considerations are just an example of how a indicators classification based on the CE strategies allows to carry out an analysis useful to compare different possibilities of implementation of the Circular Economy and to underline the main aspects that characterize them.

Standard, tailored

For years the literature has been divided between those who defend standard indicators for sustainability and Circular Economy assessment and those who are in favor of a more tailor-made approach. The development and implementation of tailored CE assessment frameworks allows companies to focus on the most relevant aspects of their core business. This is in line with the long-standing finding in the field of sustainability assessment that indicators should not be limited to general standards and methodologies but should reflect instead the business realities of a particular organization (Keeble J.J. 2003). Roos Lindgreen et al. (2022) underline how the lack of relevant benchmarks and standards represents a considerable barrier for many companies to conduct Circular Economy assessments, thus prompting a call for some forms of framework and reporting standardization. However, if standardization was to occur in an overly prescriptive way, companies would risk losing sight of aspects particularly relevant to their specific organization or industrial sector. At the same time, recent studies on CE assessment and reporting guidelines have observed how companies selecting their own Circular Economy indicators entails the risk of possible greenwashing incidences (Opferkuch K. 2021, Pauliuk S. 2018). Indeed, if companies have the chance to cherry-pick CE indicators, the risk is that they will report more based on their own purposes and intentions rather than to measure the actual performance. Kühnen amd Hahn (2018) therefore conclude that, although a normative consensus is necessary to define which metrics must necessarily be considered, companies should adapt the rest of the indicators to their own context while accepting that many of them might not be comparable with those of other companies. This compromise is even more necessary if considering that a transdisciplinary involvement of stakeholders is often necessary for the Circular Economy assessment. Although it is not yet evident in the literature how companies adapt CE assessment to their own context (WBCSD 2018), it is clear that the involvement of third parties is a key element in this process, especially with regard to consultancies, universities and supply chain partners (O. K. Roos Lindgreen E. 2022). In such collaborations, universities often provide knowledge (Pereira A. 2021), supply chain partners are mainly involved in data collection (Brown P. 2019), while instead consultancies help companies to adapt existing assessment approaches to their own corporate realities.

Other classifications

The literature analysis highlighted other frequent classifications of indicators among the articles. Among these, (Vinante C. 2021) proposes a framework to understand which functions of a company are affected by the indicators, while (P. D. Kravchenko M. 2021) classifies Circular Economy metrics based on which business processes they impact. Obviously, the advantages and drawbacks of adopting these classifications are analogous to those of micro indicators explained before. Moreover, Niero and Hauschild (2017) stress the importance of selecting the correct indicators based on whether the aim is to make strategic, tactical or operational decisions. De Oliveira et al. (2021) reflect instead on the difference between indicators for internal information purposes and those that, on the other hand, are necessary for external reporting. Finally, some authors state that it is necessary to adapt indicators based on the type of material cycles they are evaluating, given that the Circular Economy strategies belonging to biological cycles show very different characteristics compared to those of technical cycles (Parchomenko A. 2019, Rocchi L. 2021).

Table 4 provides a summary scheme of the main classification analysed and their core contributions.

Table 4 – Summary of main classification approaches

Nano, micro, meso, macro	Allow to capture the target and specific influence of the assessment. Each level can give more details on the environment in which strategies are used.
Ex ante, ex post	Allow to choose the scope of the assessment. Leading assessment can offer information about potential impacts while lagging one can analyse the effective output.
Environmental, economic, social	Allow to structure the assessment toward Sustainable Development. Each aspect needs to be addressed to achieve an effective Sustainable Development.
CE strategies	Core classification in circular assessment. Allow to identify the impact of the assessment. Each strategy requires approaches to adopt to address it.
Standard, tailor	Allow to consider the business' realities and requirements during the assessment process.

2 Literature Review Agri-food sector

In parallel to performing the literature review on the concepts of sustainability and Circular Economy, an analysis of the agri-food sector was also conducted, chosen because of its considerable relevance for the impact it generates in sustainable terms.

The aim of this chapter is to present the industry and to highlight key characteristics of sector and of organizations operating in it, which influence the assessment of potential sustainable and circular actions adopted. The need of identify these elements derived from the contingency theory presented by Sousa and Voss (2008) and revised by Leon Bravo et al. (2021), which affirm that companies adapt their behaviour based on contextual factors.

Section 2.1 presents what agri-food industry means, focusing especially on supply chain dimension (paragraph 2.1.1). Instead, in section 2.2 the implications of sustainability and CE in the sector are addressed, focusing on the latter aspect in terms of main benefits, challenges, and the methodologies implemented.

2.1 Brief description of the sector

The food industry is a crucial component of any country's economy since it produces a product that will always be in demand.

Agri–food sector fits within the broader food systems, defined by European Commission as the systems which "embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and disposal (loss or waste) of food products that originate from agriculture (including livestock), forestry, fisheries, and food industries, and the broader economic, societal, and natural environments in which they are embedded" (von Braun J. 2021).

The agri-food sector can be described more precisely as a system which focuses on agricultural products and livestock, from their production and generation to consumption. Other activities included into the supply chain concern manufacturing, distributing, and retailing processes. Four typologies of agri-food supply chains can be identified: diary, agriculture, fish breeding and livestock farming (Esposito B. 2020).

Five functions can be recognized in the sector in order to provide the nutritional needs to the population while preserving and maintaining the vitality and reproduction of the areas: economic, social and cultural, ecological, innovative and informational (Krylatykh E. 2011).

Production to meet population needs and ensure food security is an example of economic function. Other activities include the use of productive resources from other sectors and participation in linkage development, the operation of agricultural markets, establishment, and regulation of financial flows, as well as the contribution to the national GDP and other macroeconomic aggregates.

Social functions include improvement of living conditions, social infrastructure, preservation and resurgence of society's cultures and values.

Ecological function comprises the management in agricultural production of land and soil fertility, water, flora, and fauna to guarantee the best environmental balance and regime.

The demands and potential of genetic engineering, biotechnology, the safeguarding of living things, and other new developments in agriculture are reflected in the innovation function. Biotechnologies are also applied in the area of agricultural raw materials to guarantee quality and safety.

Agri-food sector performs informational functions through generating information for other areas as well as receiving, processing, and utilising a significant amount of information as part of the implementation of the aforementioned functions. The effectiveness of management choices and the execution of all functions determines the promptness of receipt and transmission of its reliability.

Food supply networks are distinct from other sectoral supply chains due to the peculiar nature of their design and work toward their objective of providing goods to final consumers in very dynamic situations, guaranteeing safe products available for consumption. Several factors can impact the achievement of the results, generate complexity in operation management and uncertainty of business performances. They may be related to the intrinsic features of the products, or to the surrounding external system, such as industrial, governmental, economic, political, environmental and social elements (Leon Bravo V. 2021). The most relevant will be discussed below.

A key attribute of food products is its perishability. As soon as the item has been harvested or leave the production phase, it begins to perish and it is essential to ensure that it reaches the last stage while retaining its properties and without spoiling, so that it can be safe to consume. Food life can change depending on whether it is fresh or preserved raw material, or used in the preparation of other food, increasing the dwell time within the chain (Dani 2015). Authorities and government, through inspections and requirements, play a critical role in this context since they control strictly the processes and avoid any disruptions, which can be disastrous (Zhang X. 2013).

A second aspect related to the nature of the product is the heterogeneity of items. Each specific product is characterized by flavour, fragrance, look, and colour, which can vary greatly even within the same product type (Dani 2015). On one hand, this provides variety in consumer choice, but on the other hand, it complicates the management of material flow along the chain with regard to transport or storage.

For what concern the external impacts, the quantity and quality of production are not easily controlled by humans, since they rely on natural ecosystems conditions (Zhang X. 2013). Climate and seasonality are core aspects to take into consideration: the strategic and operational decisions that companies have to make regarding production cannot be determined solely by market demand and customer requirements but are greatly impacted by the availability of resources based on the seasons or weather conditions. These can generate unpredictability and therefore require a great deal of risk management. Water availability can be a direct consequence of the seasonality issue: decision makers can choice the best management practices of irrigation, but the quantity of the resources is based on the actual possibility (Velasco-Munoz J. F. 2021). Controlling activities can be performed to mitigate the risk associated to uncertainty, but data management and collection in terms of input-output materials and products is difficult to perform because it often also concerns other actors along the chain and requires their contribution. ICT and new technologies are more and more adopted by producers and manufacturers to gather and exchange information and achieve effective and useful results (Ganeshkumar C. 2017). Beyond these factors, the regulatory environment, level of technology, production system, and social expectations are all significant (Zhang X. 2013), especially regarding price volatility due to risky goods.

A market macro-trend that has been emerging more and more in recent years concerns the health challenge, which affects all sectors of the food industry across the board. An analysis was conducted on 900 texts acquired from the main websites and national (40%) and international (60%) magazines specialised in food and beverage between 2015 and 2019. The most recurrent topic at international level is food safety (18%), followed by traditionality (17%), global trends in the sector (14.5%) and innovation (14%). Italian companies, in response to this growing trend, are increasing their offer of healthy products (40% of the offer) in terms of raw materials with organic origin, minimally invasive processing, reduced containment of artificial additives and preservatives, and increased health benefits for consumers (Garzia 2022).

2.1.1 Agri-food supply chain

Across industries, supply-chain systems are innately complicated due to the interaction of diverse activities with various, possibly at odds aims and the numerous linkages between material and information flows. In the food scenario, their role is even more critical because they consider both inbound and outgoing fragmented networks of firms, resources and information, their interlinked value-adding activities working to make food available in terms of time and quality.

The general activities performed regard extraction, production, aggregation, distribution, transportation, storage, consume, and disposal food products from the point of harvest to the consumer (von Braun J. 2021).

A clear representation of agri-food supply chain (or food system) stages is provided by Dani (2015) and shown in Figure 3: The producer is where the food supply chain begins, and the agri-food sourced at this point goes via various processing techniques in order to reach the final costumer. Numerous logistics and transportation firms support the movement. Analysing these activities through NACE standards, they can be classified in primary and secondary: input companies, farmers, breeders and fishers, food processors, retailers, food service (i.e., caterers) and final consumers as primary ones, while wholesalers, traders and other support figures as technology suppliers and service providers, as secondary (Eurostat 2006).

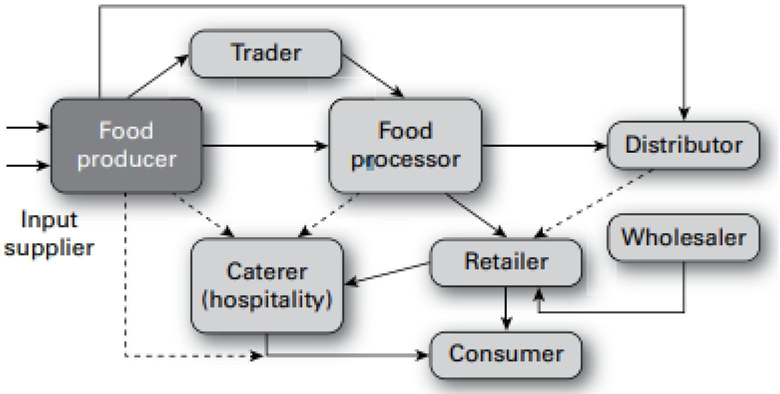


Figure 3 - Actors in a food supply chain (Dani 2015)

The agriculture sector is concentrated in the first phase of the chain. It includes the activities necessary to grow or manage the agri–products and move them to the processor phase. The actors involved include input suppliers, landowner, farmers, breeders and fishers, traders and direct markets. The output generated regard animal proteins (meat, fish, dairy), fruits and vegetables, commodity crops, global commodities (coffee and cocoa), processed food of plant origin (wine and oil) (Dani

2015). This phase is relevant since it is getting to the consumer faster and in a variety of ways thanks to operational effectiveness, food safety, food quality, innovation, and new business models. Moreover, producers are the most affected by all criticalities mentioned above that characterise the high complexity of the agri-food sector, contending with climatic weather patterns that are becoming more unpredictable, lack of water, and soil degradation brought on by industry and urbanisation (Yadav V.S. 2021). Other issues can regard the intrinsic value of the product, as the perishability, which can be faced thanks to the adoption of packaging and processing methods to increase the longevity of the lifecycle. The lack of adequate finance, regulatory environment, the role of public and private sector and the collaboration between entities can be identified as the main barrier to the development of the sector. (Bloemhof J.M. 2015, Dani 2015)

The following stage regards the manufacturing processes needed to transform the material provided by the producers into a final product suitable for the costumers. This phase is different based on the typology of products considered: some typologies of food just required packing to make it easier to transport it through the logistics system, others can require more processes to turn it into ready-to-eat meals. Overall, three main operations are included: the effective processing to the food to transform it, the packaging and inventory management. Preservation, safety, variety, convenience and improvement are the main goal of the processing operation. Packaging has not only the functionality to preserve a food, but also to promote it from a marketing perspective. This second purpose is increasingly bringing with it environmental issues related to the excessive use of materials. Inventory management has environmental impact due to the critical management of food safety which can incur into food loss. The problem can emerge regard chemical aspects, due to the incorrect temperatures or standards at which food is kept (Dani 2015).

The value chains of the four main agri-food categories mentioned above (dairy, animal, agriculture, fish farming) show some similarities and distinctive elements. They are characterised by the potentiality of selling the good to the end customer directly without further processing or selling it to manufacturing companies to process it and create value – added products from raw materials, that are more complex in terms of ingredients contained. Diary, animal and fish value chains have to deal with veterinary controls and standards along the whole chain. Each typology has a specific process to treat the goods and keep them unaltered (Amicarelli V. 2021, Dani 2015).

The supply chain is linked to the ultimate consumer through the retail environment. This stage includes markets and caterers. The critical point regards shelf life and data labelling which influence food loss and waste management, but also price fluctuation and a lack of standardized offers for some products (Dani 2015).

The transportation of the good is a relevant stage of the supply chain in terms of materials involved for the integration of processes and the movement across the different phases just mentioned. The inefficient logistic and handling management systems can generate food waste on food safety. The transfer of goods must be done in a manner that keeps them safe from tampering and maintains their quality, limiting cold chain deficiencies and improper cooling. It can be also assessed that information technology is significantly reliant on the modern retail logistics system, allowing to transport of larger amounts of food more quickly and over longer distances. Correct implementation of traceability or other advanced technology systems allow to increase transparency and so food safety, such as the introduction to reverse logistics logic (Yadav V.S. 2021).

Overall, supply design must consider some aspects which can allow obtaining resource efficiency: the creation of an integrated network of warehouses to increase control and connection, reduce time waste obtaining better handling systems for inventories, always remember about the perishability of the food (Dani 2015). Some issues could be addressed by optimising the position of supply chain nodes, opting for more sustainable alternatives in all phases of food distribution, enhancing food distribution routes, and better restructuring of the food logistic chain network (Yadav V.S. 2021). Moreover, as reported also by Gallo et al. (2022), collaboration between firm and suppliers, customers, competitors, and other organizations has relevance importance in order to pursue efficiency.

2.2 Sustainability and Circular Economy in the agri-food sector

The following paragraphs presents the main sustainability and circularity aspects related to the agri-food sector, in terms of issues (paragraph 2.2.1) and possible solutions (paragraphs 2.2.2 and 2.2.3).

2.2.1 Unsustainable practises: state – of – the – art

Agri-food sector is a crucial industry because of resource-intensive exploitation over the previous years to support a rapidly expanding population while promoting urbanisation and economic growth.

Total global food demand is projected to increase by 35% to 56% between 2010 and 2050 (van Dijk M. 2021) and the industry must be able to respond accordingly to meet this demand.

First, it has to ensure food security, which has been defined as the condition "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 1996). The assessment of the global level of food insecurity is significantly hampered by the unprecedented COVID-19 epidemic in 2020 and its ongoing effects in the following years. According to recent data collected by FAO (2022), between 702 and 828 million people worldwide—or 8.9 and 10.5% of the total population—experienced hunger in 2021. The prevalence of undernourishment PoU, defined as "the proportion of the population whose habitual food consumption is insufficient to provide the dietary energy levels that are required to maintain a normal active and healthy life" (FAO 2020), has increased from 8.0% in 2019, to 9.3% in 2020 and 9.8% in 2021 on a global scale. 55.3% (425 million) and 36.2% (278 million) of the world's 768 million undernourished people will live in Asia and Africa, respectively, while less than 8% will reside in Latin America and the Caribbean (57 million) (FAO, IFAD, UNICEF, WFP and WHO 2022).

Another internationally comparable estimation regards "the proportion of the population facing moderate or severe difficulties in accessing food" in quality and quantity perspective due to lack or money or other resources (FAO 2020). This indicator, prevalence of moderate or severe food insecurity, shows that estimated 29.3% of the world's population, lacked access to enough food in 2021, 29.5% in 2020 and 25.4 in 2019. More than 350 million more individuals experienced moderate or severe food insecurity in 2021 compared to 2019, the year before the COVID-19

pandemic broke out, even though the population remained largely consistent between 2020 and 2021. At the regional level, contrasting trends were observed from those at the global level, where levels of moderate or severe food insecurity remained consistent. Between 2020 and 2021, Africa experienced the largest growth in moderate or severe food insecurity, 57.9%, followed by Latin America and the Caribbean, 40.6% (FAO, IFAD, UNICEF, WFP and WHO 2022).
Both the indicators mentioned target SDG 2 "Zero hunger", striving to achieve by 2030 accessible food conditions for everyone.

The demand for food production to ensure security and compensate for deficits has environmental consequences (Silvestri L. 2022).
From recent analysis, it emerges that more than 90% of land- and water-related environmental consequences are attributable to agriculture.
Globally, irrigated agriculture accounts for 70% of all water abstraction and a disproportionate amount of water consumption in irrigating nations (Gruère G. 2018) and thus becoming the world's largest consumer of freshwater resources (Ellen MacArthur Foundation 2019). Moreover, agricultural operations continue to be a significant source of water pollution, water risks are becoming more prevalent in agriculture and have a significant impact on production, so reducing the quantity of water required for irrigation can significantly improve total water use efficiency (FAO, UN water 2021).
Soil degradation is another consequence primarily caused by agriculture. Watts et al. (2017) claims that the main reason of the 24 billion tonnes of fertile soil loss every year is destructively intensive agriculture. Due to intensive tilling, frequent harvests, and extensive chemical use that boost yields at the price of long-term sustainability, this trend has emerged (Watts J. 2017). Usage of pesticides has also a significant role in human toxicity, due to farm workers' exposure, and air quality degradation (Ellen MacArthur Foundation 2019).
For what concern energy, food production and supply utilized more than one quarter of the energy used globally, due to demanding activities like the movement of agricultural machinery, transportation, and the needed for the main crop production. The percentage of renewable energy used in farms is an important factor, considering that the level of technology and alternative source of energy can have an impact (Del Borghi A. 2020, Zadgaonkar L.A. 2022).
These statistics represent the current production situation, and it is clear that if the production output were to increase, these problems would also grow.

The problems mentioned also stem from the fact that so many products throughout the supply chain are wasted and lost. High Level Panel of Experts on Food Security and Nutrition (FAO 2014) presented a clarification between "food loss" and "food waste" terminologies, although it should be noted that some authors claim to use these two terms as synonyms. Food loss is intended as "decrease, at all stages of the food chain prior to the consumer level, in mass, of food that was originally intended for human consumption", it occurs at the first stages of the supply chain usually due to organisational and technical constraints. Agnusdei et al. (2022) present a clear distinction between qualitative and quantitative food loss, affirming that the former arises when the quality of the product is potentially perceived as low by consumers due to colour, dimension or flavour features, while the latter occurs when there are physiological or mechanical deterioration of the product.

On the other hand, food waste refers to food appropriate for human consumption being discarded or left to spoil at consumer level.

Target 12.3 of SGD aims at halving the per capita global food waste by 2030, increasing the attention to this problem. The percentage of food lost globally after harvesting at the farm, during transportation, storage, wholesale, and during processing was 13% in 2016 and 13.3% in 2020. According to these percentages, the food loss index is 98.7 in 2016 and 101.2 in 2020 (FAO 2020), while an estimated 17% of food is wasted at the retail and consumer levels (UNEP 2021). Depending on the degree of industrialisation of a nation, these inefficiencies typically arise at various points throughout the supply chain. Food is wasted and lost primarily in later stages of the supply chain in high-income countries. On the other hand, early inefficiencies in the food value chain are more common in emerging nations (Muscio A. 2020).

Several drivers have been identified as the key important factors that will affect the scope and character of the issue in the future The International Food Policy Research Institute (IFPRI) claims that unfavourable weather, climate change, inadequate pest management skills, limited access to technologies, and inadequate infrastructure for storage, transportation, and processing, are to blame for waste inefficiencies (IFPRI 2019). The dimension of time is another relevant feature to consider. Food can decompose and become waste in shorter period of time compared to other materials (i.e., glass, metals, paper, plastic). The transition time from edible food to waste is so a crucial point of analysis to consider (Papargyropoulou E. 2014).

The relevance of this issue is due to the strong impact and considerable consequences it has in environmental, economic and social terms (Papargyropoulou E. 2014).

When food waste is disposed in landfills, its natural decomposition process produces methane and carbon dioxide which are harmful GHGs contributing to climate change (Buzby Jean 2022). Moreover, it should be considered also the embedded impacts of all the activities in the previous life cycle stages of food before it became waste, such as agriculture, processing, manufacturing, transportation, refrigeration, storage and retail, they already generate damage to the environment, so waste worsen them (Padfield R. 2012, Tuncer B. 2011, Lundqvist J. 2008).

Furthermore, several studies highlight that food waste has also a substantial economic impact for everyone in the food supply chain (Evans D. 2011, WRAP 2011, Morrissey A.J. 2004). Gustavsson et al. (2011) and Lundqvist et al. (2008) emphasize that avoidable food losses have a direct and negative impact on the income of both farmers and consumers. This economic impact is mainly linked to production and purchasing costs, as well as costs associated with the final disposal of food waste. Therefore, improving the efficiency of the food supply chain should be a priority to reduce the production cost of food and thus make prices more affordable for consumers (Papargyropoulou E. 2014).

The economic aspect becomes more relevant when looking at data on the type of business operating in the sector. According to the most recent estimates, there are more than 608 million family farms in the world, which account for between 70 and 80% of all arable land and produce roughly 80% of all food consumed globally. Based to the new research, approximately 70% of farms operate on less than one hectare of land, which records for just 7% of all agricultural land. Another 14% of farms, which control 4% of the land, are between one and two hectares, and 10% of farms, which control 6% of the land, are between two and five hectares. More than 70% of the world's farmland is managed by the largest 1% of farms, which are larger than 50 hectares; over 40% of agricultural land is located on farms larger than 1000 hectares (FAO 2021). The fragmentation of the sector just shown brings with it economic problems in terms of accessibility of financial resources, so companies must also try to limit waste in order to save on costs. Therefore, investments in agriculture are necessary to help smallholder farmers and processors increase on-farm production effectiveness, post-harvest and processing procedures, and trade and marketing of agricultural products. It is essential for international organisations and policy makers knowing these data in order to create investments and public policies that support family farming, boost the productivity of smallholders, and enhance rural lifestyles (Ganeshkumar C. 2017).

Last, in addition to environmental and economic impacts, food waste also has social and moral implications (Salhofer S. 2008) highlighted by the disparity between food poverty and food wastage in a context of fast-growing population and diminishing natural resources. Some authors attribute the production of food waste to the behaviour of providers and consumers, whose role is crucial especially in industrialized countries (Esposito B. 2020).

Unsustainable consumption leads to negative decisions on production and impact on the environment because more land, water, fertiliser, and fossil fuels are needed to create these extra calories (EEA 2012). The equivalent of 3.3 earths would be required to support global consumption if everyone used resources at the same rate as those in OECD and EU nations. At least five earths would be required if everyone consumed resources at the same rate as those in Canada, Luxembourg, and the United States (UNICEF Office of Research 2022).

Overconsumption is defined by Global Food Security Agency as "a state in which food intake exceeds individual requirements, commonly resulting in malnutrition, overweight and obesity" (GFS 2016). The present definition of food waste excludes overnutrition, while numerous authors argue that food consumed in excess of individual needs should be considered waste and deserves the same concern as all other forms of food waste, necessitating a better understanding of its social, environmental, and economic consequences, both individually and collectively (Silvio F. 2022). Overconsumption leads to obesity, and its rate is rising since an increasing number of people consume food that exceeds the recommended caloric intake. A clearer understanding of the scope of overnutrition and its environmental consequences can aid in the distribution and adoption of more sustainable food consumption habits. Individually, increasing attention to environmental issues is likely to induce more attentive eating habits (Silvio F. 2022). Ganeshkumar et al. (2017) also suggest that agro-based businesses can only succeed if consumers are informed about healthy eating habits, encouraged to prefer locally grown and preserved food, and the agricultural industry implements good and well-maintained SCM processes. Indeed, food security is an increasingly global issue that raises questions about the ethics of wasting food that could have otherwise been used to feed people (Lang L. 2020, Stuart T. 2009).

The other major branch of the agricultural sector, along with organic products, is livestock breeding.

40% of total agricultural output in developed countries and 20% in developing one is accounted by livestock, supporting the livelihoods of at least 1.3 billion people worldwide providing 34% of global food protein (FAO 2022).

Based on this data, it can be commented that proper livestock management is necessary. FAO promotes indicators "risk status of livestock breeds" or "proportion of fish stocks within biologically sustainable levels" of "illegal, unreported, unregulated fishing" to control the data and improvements (FAO 2020).

Moreover, American Veterinary Medical Association defined animal welfare as "how an animal is coping with the conditions in which it lives. An animal is in a good state of welfare if (as indicated by scientific evidence) it is healthy, comfortable, well-nourished, safe, able to express innate behavior, and if it is not suffering from unpleasant states such as pain, fear, and distress” (AMVA 2022). In the context of breeding, these rights are often not respected, especially in intensive farms.

Consequence on environment emerges not only from past data, but also from future forecasts: the demand for water, energy, and food is expected to rise dramatically over the next few decades, according to different projections, while the natural resource base will also be undermined by environmental degradation and climate change in order to face with the global population increase expected in the coming years (Del Borghi A. 2020).

The need to implement a sustainable approach is also dictated by the necessity to preserve the functions this industry has, as presented above. Three out of five functions are very close to the concept of sustainability, as described in the first chapters: economic, social and environmental. Adopting sustainable strategies helps to ensure that the sector is able to continue to perform those tasks efficiently also in the future.

2.2.2 Sustainability assessment of food production systems

The need for change has been increasingly emerging for some time. Sustainable food system (SFS) configuration was introduced by FAO, defining it as a food system that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised. This means that it is profitable throughout (economic sustainability); it has broad-based benefits for society (social sustainability); and it has a positive or neutral impact on the natural environment (environmental sustainability) (FAO 2018). One of the last declarations from international authorities was during Food System Summit in 2021, when UN promotes the idea that changing food system and turning it into a sustainable one is one of the most impactful approaches to adopt to address climate change and restore biodiversity. This new system will contribute to food security for all while protecting the environmental, social, cultural, and economic foundations that provide food security for future generations, and so pursue Sustainable Development (von Braun J. 2021).

Although there are innumerable models for sustainability assessment in general, no internationally recognised standard clearly specifies what sustainable food production comprises and how to achieve it (Vermeyen V. 2021). Additionally, there is no universally agreed-upon definition of the minimal standards necessary for an agri-food business to be considered "sustainable” (FAO 2014).

In order to bridge the gap between different sustainability tools and promote collaborations for the long-term transformation of food systems, FAO developed

Sustainability Assessment of Food and Agriculture Systems SAFA (FAO 2014), while Energy – Water – Food Nexus allows to create an integrated vision of these three critical resources. Another relevant nexus concern climate change, land availability and energy. This "trilemma challenge" is proposed by from Harvey and Pilgrim (2011) and echoed by Silvestri et al. (2022), which poses attention to these three main issues preventing the sustainable development of global economies.

SAFA is a holistic global reference model composed of a number of levels that are nested to improve coherence throughout. The high level "themes" presents 21 sustainability issues which must be addressed in the assessment and explicit them through the themes goal definition. Each theme is better present by several "sub-themes", which overall are 58, and the corresponding default indicators that specify the quantifiable requirements for the sub-sustainable theme's performance. It mostly builds on already-existing sustainability schemes, giving businesses the chance to utilise data already available and merging efforts with other tools and sustainability initiatives.

Compared to the sustainability assessments presented in Chapter 1.3.2 that still differ on what constitutes a sustainable food and farm system, this proposed framework allows to focus on the evaluation of food supply chains and companies which work in it covering all the sustainability dimensions relevant for the sector and even adding the governance aspect as well. Instead, other tools (i.e., LCA, MFA, …) are more specialised in products perspective, emphasising their life cycle and material flow and lacking in the capture of integration aspect of the entire value chain, which is a critical element of the food sector and therefore requires the proper attentions. On the other hand, the model excludes consumers and end-of-life managers in the scope, as SAFA does not evaluate product-specific sustainability, wherein inclusion of these stages would be relevant.

Assessment process develops in four steps: "Mapping", "Contextualization", "Indicators" and "Reporting". The first step is required due to the complexity of food value chain; by mapping it, it will become clearer what is being measured, where the enterprise's sphere of influence and direct control ends, where organisational and operational boundaries are, and how the production network interacts. Huge quantity of information is obtained, so "contextualisation" phase allows to adjust sub-themes and indicators measurements and ratings and clarify if they are appropriate for the situation around the object being evaluated. In contrast to the indicators collected from the literature analysis presented in the previous chapter, SAFA promotes indicators that capture more organic and less technical aspects to reflect the nature of food products along the whole supply chain. Even if 118 indicators are included in the model, FAO states that the assessor must create customised indicators in addition to the SAFA default indicator set to assess performance at intermediate performance levels according to the context. The last step provides an answer to the major problem that has arisen repeatedly concerning the creation of a single, comparable assessment end result, synthetized the information entered. Enterprise's actual performance is obtained as output, rather than relative advancements over time. The need that reports be released in their entirety, with scores on all SAFA objectives judged relevant, and with all assessment steps and selected indicators made transparent, is a key component of the SAFA Guidelines.

The increase in world population and the resulting demand for food, water and energy are exerting increasing pressure on natural resources and ecosystems. In this context, the Water – Energy – Food nexus aims at highlighting the linkages between water, energy and food production systems, in order to assess their environmental sustainability and to inform new transformative strategies and policies based on Circular Economy (Jacob C. 2021). An intervention in one of these three sectors may induce positive or negative consequences on one or both other sectors. Therefore, it is essential to identify the optimal approaches that allow to optimize the reduction of the cross-sectoral environmental impacts. Moreover, Del Borghi et al. (2020) highlight the importance to apply a life cycle thinking in order to understand the interconnections in the nexus along the whole supply chains. Adopting an even broader view, some other studies affirm that a nexus approach requires coordination and integration even across levels of government and across sectors, emphasizing the importance of institutional relationships and effective coordination mechanisms (Scott A. 2017, Weitz N 2017).

It is clear that food production has a strong impact on the WEF nexus, since it significantly contributes to the consumption of natural resources throughout its life cycle. Indeed, the European Common Agricultural Policy (CAP) (European Commission 2013) sets targets for agriculture according to three priority areas for intervention in the WEF context: the preservation of biodiversity and the management of 'natural' farming and forestry systems, the management of water resources, and the facing of climate change. Moreover, it is worth mentioning an interesting study performed by Del Borghi et al. (2020) to identify environmental hot spots in the whole life cycle of some food products. The results are expressed through a set of impact categories, which can be read also as stand-alone indicators, identified to pave the way for WEF nexus quantification: water scarcity index, global warming potential, non-renewable cumulative energy demand and toxicity potentials.

Reducing waste and extending lifetime of products and materials through Circular Economy strategies allows to reduce energy consumption and other environmental impacts, thus minimizing the WEF nexus. Hence, the Circular Economy and the nexus are closely linked (Stijn R. 2017). According to the authors, "the use of a CE framework can accelerate the adoption of a nexus thinking, recommending a system integrated perspective through the analysis of the full lifetime of products". On the other hand, the fact that CE and the WEF nexus are closely linked does not mean that it is easy to identify which CE strategy is the most beneficial for the environment.

2.2.3 Circular Economy implementation in the agri-food sector

As support to the sustainability tools to achieve Sustainable Food System, Circular Economy is considered an effective solution to be introduced into the agri-food sector by a wide number of authors and international organisations, since it allows to minimize the external inputs required, close the loops in the production, reduce waste and emissions, utilise resources, raw materials and energy more effectively, protect natural resources by exploiting and valorising them once more in a way that generates the most economic benefit and the least amount of environmental destruction (Muscio A. 2020, Zadgaonkar L.A. 2022, Zhang X. 2013).

It is important to stress that CE in food systems is exceptional because food products are biological and single use. Increasing and extending product use is a broad CE concept meant to reduce the number of items needed, but this concept cannot be extended to the food system.

Here below, some strategies and approaches to implement Circular Economy in the agri-food sector and some attempts found in literature to measure the circularity level of these solutions are discussed.

In order to meet everyone's nutritional needs, a circular food system essentially means reducing the material demand and associated environmental impact of the products in this system over the course of their existence. Policy Research Centre for Circular Economy develops a monitor to guide the transition to a circular economy and provide a first set of indicators to monitor the food system (Vermeyen V. 2021). It states that the key to obtaining a CE for food is to maximise the value of i) inputs, ii) products (i.e., food), and iii) residual streams across the whole supply chain stages. Strategies to reduce the material demand and related environmental effects of the food system are investigated for each of these areas and represented in Figure 4Figure 4.

Regarding the first aspect, a CE for food would maximise input efficiency while maintaining food security by optimising total land use, total use of other inputs, and total use of other inputs.

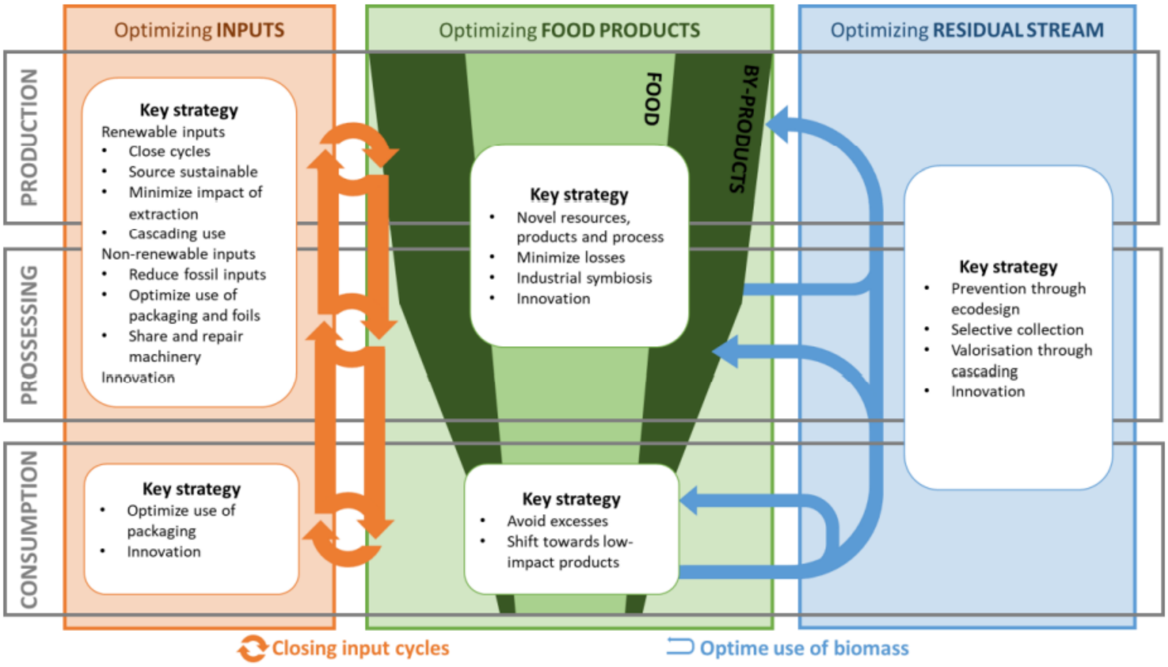


Figure 4 - Schematic overview of CE for the food system (Vermeyen V. 2021)

In order to maximise the utilisation of food items, the CE searches new methods to better satisfy customer dietary needs. By doing this, the same dietary requirement can be met with less manufacturing, hence lowering the material requirement and its effects. Avoiding excesses and selecting products with little environmental impact are the two main tactics that may be used to achieve this. Due to their single-use and biological character, the items in the food system are distinct from other CE items. Common CE tactics, such as eco-design, repair, sharing, and reuse, applied to increase the number of uses per product, cannot be used with this system. CE for food, on the other hand, makes sure that biomass is applied at the maximum level feasible in order to maximise its utilisation in the system. A well-known framework for doing this is the cascade of value retention.

The framework offers a single point of departure for the various stakeholders working across policy areas on the various facets of CE for food and can be used to guide future policy actions.

Food waste prevention and management frameworks

Several international directives suggest concrete actions to implement Circular Economy in the agri-food sector, such as Article 9 Directive (EU) 2018/851 which establishes provisions for tackling food wastage. Those measures shall promote and support sustainable production and consumption models, reduce food waste and prioritize food donation and other redistribution for human consumption over animal feed and reprocessing into non-food products. In order to achieve that, Member States shall provide fiscal incentives for food donation, develop and support information campaigns to promote waste prevention and raise awareness among citizens, and possibly establish specific rules for measuring food waste. About the last point, different initiatives, projects and instruments have been developed globally and in the EU in order to enhance the consistency and quality of food waste data. Among others, the Food Loss and Waste Accounting and Reporting Standard (FLW Protocol 2016) aims to facilitate the quantification of food waste by providing a flexible framework which establishes uniform terminologies and measurement methods while still allowing its users to choose the most appropriate scope for data generation (Gillik S. 2018, FLW Protocol 2016). However, Garske et al. (2020) underline the current absence of a quantified, measurable and thus sanctionable reduction target for food waste. In this direction, the proposed Farm to Fork Strategy represents a first attempt to introduce legally binding reduction targets (European Commission 2020). However, this kind of objectives should be introduced by all Member States in order to encourage and accelerate the adoption of Circular Economy practices and increase their effects on reducing waste.

Following the introduction of these international directives, several frameworks have emerged to tackle food wastage. Among these, the Food Waste Hierarchy (Figure 5) represents a key reference framework to implement Circular Economy into the agri-food sector. It allows to identify and prioritize the options for the minimization and management of food surplus and waste throughout the supply chain (Papargyropoulou E. 2014). Ranging from most to least preferred, the proposed hierarchy consists of six levels starting with prevention as the most attractive option. Although it requires a fundamental re-think of the current practices to minimize food waste, it shows the higher potential to deliver substantial environmental, economic and social benefits. The second most attractive option is donation, which involves the distribution of food surplus to groups affected by food poverty, followed by the option of converting food waste to animal feed. The last three options are then recycling (e.g., for industrial uses), other recovery (e.g., for energy production) and disposal.

It's worth noting that the top three actions can be undertaken before food constitutes waste (Garske B. 2020). Based on this consideration, Papargyropoulou et al. (2014) clearly defined the distinction between waste prevention and waste management. While the first approach includes activities aimed at avoiding waste generation, the second one instead includes the strategies to deal with food waste once it has already been generated. Of course, waste prevention should be set as a priority to achieve an effective circular model, but unfortunately it is a much more difficult approach to implement with respect to waste management.

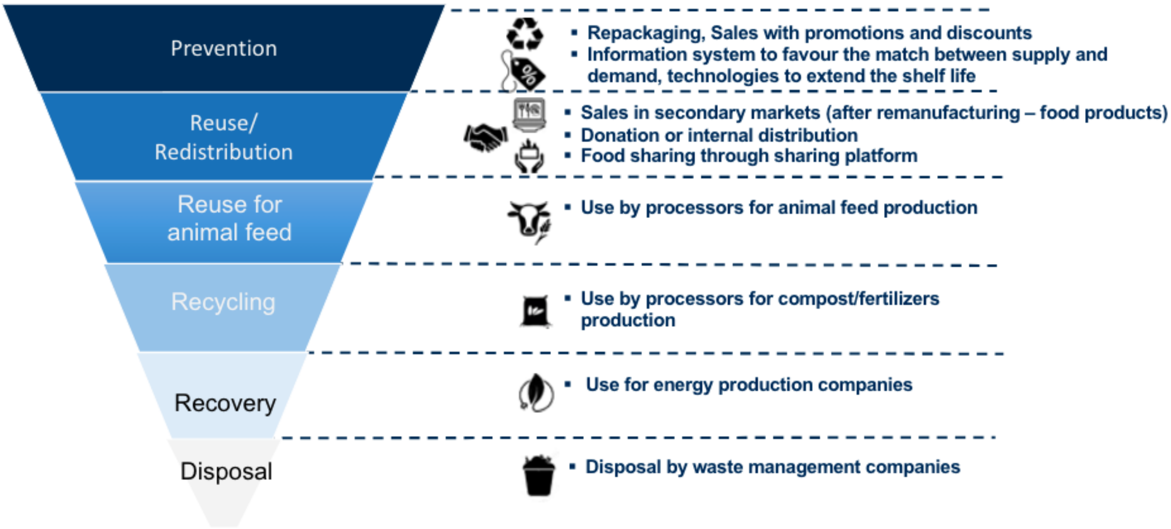


Figure 5 – The Food Waste Hierarchy, re-adapted from Food Waste Measurement readapted from (European Commission 2020)

Although the European Waste Framework Directive (European Parliament Council, 2008) advises the Member States to consider all the three pillars of the Triple Bottom Line at the same level, the waste hierarchy is clearly focused on the environmental aspect. This evidence has been the subject of numerous criticisms (Rasmussen C. 2005, Porter R.C. 2002, Price J.L. 2000) which have underlined the importance of identifying the option that guarantees not only the best environmental outcome, but also the best social and economic one.

Taking inspiration from the Food Waste Hierarchy, Papargyropoulou et al. (2014) developed the Food Surplus and Waste Framework (Figure 6) introducing a further distinction between food surplus and food waste. Indeed, food surplus is often incorrectly referred to as food waste but in reality, it becomes such only when it is no longer edible. In order to reduce the amount of food surplus, the priority is to prevent overproduction and oversupply of food beyond human nutritional needs at all the stages of the food supply chain. This includes production and supply of only the necessary amount of food to cover global nutritional needs, addressing unsustainable consumption patterns and redistribution of unavoidable food surplus to groups affected by food poverty. When it comes to food waste, the distinction between avoidable and unavoidable food waste becomes central when deciding for the most appropriate waste management options. In this regard, the authors suggest a whole detailed series of possible strategies to prevent and manage both avoidable and unavoidable waste. In short, the best ways to prevent food waste in developing countries is to improve infrastructures, make production and distribution more efficient and increase skills and knowledge, while in developed countries it is necessary to increase the awareness about the environmental impact of food waste in order to incentivize more sustainable consumption practices. Once the options for prevention are exhausted, the framework suggests recycling food waste into animal feed and to opt for composting and energy recovery just when recycling is not feasible. Finally, disposal in landfill is proposed as the least favorable option for managing the remaining fraction of unavoidable food waste.

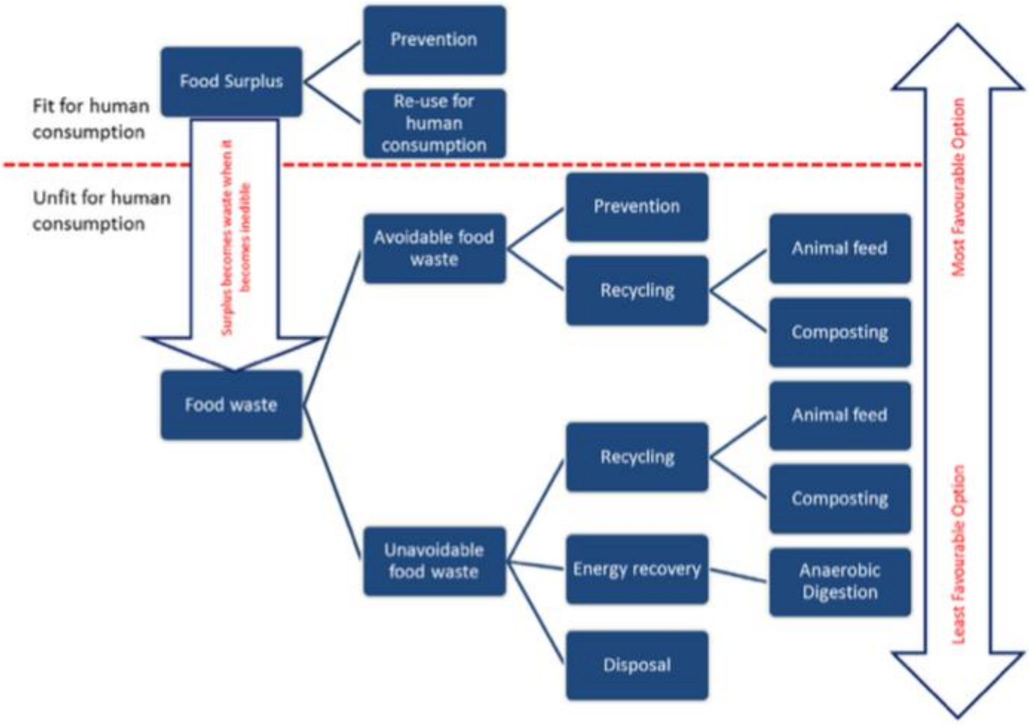


Figure 6 – Food Surplus and Waste Framework (Papargyropoulou E. 2014)

Circularity assessment

All the authors in literature state that it is essential to have the right circularity measurement tools as a support for decision making in order to develop an effective circular food production system. However, the current literature on this topic is rather limited, with an evident diversification on the sustainability focus and few existing methodological approaches (Elia V. 2017, Tsolakis N. 2018, Velasco-Munoz J. F. 2021). In addition, most of the current assessment methods require an in-depth knowledge of the company operations and sophisticated data gathering software, thus reducing their real-world applicability and managerial value. Circular Economy in the agri-food sector is indeed characterized by an enormous diversity of products which therefore makes it necessary to establish data collection standards for circularity assessment, in order to avoid irregular data and poor comparability (Zhang X. 2013). On the other hand, Kristensen and Mosgaard (2020) argue that the resources required in a company to obtain and organize the necessary data may be excessive, and therefore they emphasize the importance of combining quantitative indicators with other relevant CE information in order to ensure a complete understanding of the context.

Moreover, the fact that circular solutions often involve a larger part of the supply chain increases the risk of double counting while measuring circularity, which further complicates the uptake of Circular Economy indicators in the agri-food sector. But even though most authors argue that the adoption of CE models along the supply chain needs to be examined using a farm to fork methodology, some other writers have concentrated their research on a particular supply chain stage. For example, Esposito et al. (2020) state that retail and consumption stages are not considered enough, even though their contribution in waste generation and incorrect resource management is considerable. Gallo et al. (2022) argue instead that circularity indicators should be focused in the first production phase to evaluate the relationships with suppliers but also the traceability and the products' quality. This perspective assumes that "operating with a CE oriented vision does not only mean achieving zero waste, but also using indicators that allow selecting the best suppliers with the best raw materials and ensuring production consistent with demand", as confirmed also by Jacob et al. (2021). On the other hand, Kristensen and Mosgaard (2020) underline how the focus on single stages of the supply chain can lead to sub-optimizations where the improvements are focused on the individual company, thus missing the system perspective of Circular Economy. Therefore, a more holistic approach should be preferred in order to reflect the complexity of food system and to explore more deeply the social and economic repercussions of a choice, moving beyond the biophysical environment.

Of course, the sustainability and CE assessment methodologies presented and discussed in Sections 1.3 and 1.4 can be applied also to the agri-food sector. Zhang et al. (2013) apply for example a Life Cycle Assessment to evaluate the environmental benefits of agricultural circular economy systems. However, the particular focus of this sector on the biological side of the Circular Economy makes many of this assessment methodologies unsuitable for the agri-food industry and pushes research towards the development of other frameworks possibly closer to the characteristics of this sector. With this purpose, Rocchi et al. (2021) present a modified Material Circularity Indicator as a first attempt for the creation of an index devoted to biological cycles. MCI is the only available circular metric that attempts to take product durability into account, thanks to the calculation of the Utility Flow Index. As highlighted by Parchomenko et al. (2019), very few CE metrics include it despite this was a core principle in CE. This is probably since most of the circularity indicators in literature are designed for technology cycles, thus confirming that the development of new indexes specifically tailored for biological cycles is required.

Although the literature investigating agri-food CE metrics is still in an initial phase, some authors are starting to present frameworks to classify the indicators based on some key elements. Among these it is obviously present the typical classification according to the pillars of the Triple Bottom Line, with a prevalence also in this case of environmental indicators over social and economic ones. Silvestri et al. (2022) states that the main areas covered in the environmental analysis of CE in the agri-food sector are resource consumption, energy consumption, emissions, waste, land and soil degradation, water quality and consumption, use of chemical substances such as pesticides and impact on biodiversity and ecosystems. The same authors also classify the energy-based indicators according to the different phases of the supply chain they impact. Indeed, the energy impact of the agri-food systems is a widely debated aspect since they involve the consumption of a significant amount of energy required from agricultural machinery, irrigation, transportation, and processing. Therefore, sum aspects such as the fraction of renewable energy used in the processes (Peano C 2014) and the money invested in energy saving measures (Coppola A 2020) become fundamental to be considered for a CE assessment of agri-food systems. Other classifications of indicators are proposed by Gallo et al. (2022) which investigates in which production phases of the agri-food sector the CE indicators found in literature can be applied, and by (Veleva V. 2017) which distributes the indicators among the different levels of the Food Waste Hierarchy.

However, there are still a number of obstacles that need to be tackled before Circular Economy can be properly implemented and assessed. The issues concern areas related to legislation, reverse logistics, geographic dispersion of businesses, customer acceptance, need for technology development and spread, and investments and incentives (Velasco-Munoz J. F. 2021). In particular, governmental and legislative cooperation are essential throughout the stages of CE's implementation, especially the earliest phases. It has been demonstrated that one of the biggest obstacles for small and medium-sized companies to adopt a circular strategy is a lack of government support (Muscio A. 2020). Moreover, consumers behaviours are included in the analysis of the challenges since the consumption phase is considered in the supply chain perspective (Muscio A. 2020).

> *"The complexity of the agri-food system requires a complex set of metrics, for better understanding the right direction for making production of food more circular. We live in a planet with finite resources, including some strategic ones for the food production. Complex assessments at micro, meso, and macro levels will not lead to a solution, but they may guide us in re-thinking our way to approach to food production."* (Rocchi L. 2021)

3 Research questions and methodology development

3.1 Research questions

The increasing attention given to resource consumption and waste management issues found in the literature are of relevance in the food sector because of the required use of resources in the production, processing and management of the final good. The pursuit of Sustainable Development has been identified as the main approach to adopt to face these questions. This goal is possible to achieve through the introduction of practices based on the Circular Economy (paragraph 1.2.1), which can offer significant insights for managing resources, even if the transition from linear to circular models still presents several challenges (Cayzer S. 2017).

First, it requires to implement properly the strategies: businesses prefer to adopt defined models and patterns, such as those presented in paragraph 1.2.2, in order to follow precise steps. Then, a good level of evaluation to monitor and improve the strategies implemented is necessary (sections 1.3 and 1.4). This phase brings more significant challenges for companies not only during the assessment process, but also in the analysis of the results. The outcomes of CE assessments are used by the firms to promote external communication and offer strategic insights into resource use, and so a major effort is required in terms of capabilities in order to encode and transmit correctly this know-how that has been generated. The ability of decision-makers to gather information and use them as a feedback loop to influence decision-making assumes that they can evaluate the findings of sustainability metrics, although this is frequently noted as a challenge. Thus, the need of comprehension of company assessment capacities, matching their requirements with the current methodologies, should be assessed to lower assessment fatigue.

The situation becomes more complicated when the requirements for the production of food and the management of the product along the chain are taken into consideration, which requires sensitive attentions and practices (sections 2.1 and 2.2). The topic of circularity in agriculture has been addressed with increasing attention in the last decades. The studies show that the concepts, methodologies, and tools currently in use for evaluating waste management and resource recovery systems do not sufficiently account for the complex value of supply chain networks. Different authors suggest the participation of diverse stakeholders in co-creating evaluation methodologies and implemented them, that may have the ability to speed up toward Sustainable Development by enhancing business capacities.

Numerous research has emphasized the advantages of using indicators as the basis for assessment procedures and monitor the implementation of CE strategies. There are many practical and insightful metrics that are currently available in the literature that could be combined to evaluate the complex value. Most are composite indicators, lumping together various information and increasing the complexity of implementation, not giving more specific indications of what needs to be improved since they create an overall vision. Therefore, due to a lack of industry assistance in making systematic selections of applicable indicators from among hundreds of potentially useful and mediocre assessment capabilities and capacities, several organisations have chosen not to do a CE evaluation. Moreover, choosing the set of metrics that will be most effective at evaluating the system under investigation inside a company will require that they be simple, transparent, and easy to measure (Iacovidou E. 2017, P. D. Kravchenko M. 2021).

While focusing extensively on methodology proposals, the literature on this topic has neglected the capabilities of companies to link these theoretical approaches with practical and mainstream applications. The gap concerns the process of selection appropriate indicators. What is missing is the lack of coherence and simplicity in the pool of metrics that are now available in this area (as well as those that may have been overlooked) and the requirement for multi-dimensional evaluation of systems suitable for companies with different resource availability.

This study aims at filling this gap through two steps. The first research goal is to study the best possible indicators useful for a decision maker who wants to make the business more circular inside a food company. This research question has been addressed by creating a comprehensive framework which propose a list of simple indicators, accessible not only to decision makers within the company, but also to actors along the supply chain. The goal is closing the gap between theoretical and practical implementation challenges, identified useful, simple and homogeneous aspects for circularity implementation that best addressed the needs.

After having identified clear metrics to apply, the second research goal is to provide a methodology that will assist a user in navigating between the various indicators. This proposal would be beneficial to orient decision makers towards the aspects most relevant to them, perform multi-dimensional evaluation of systems based on different companies' capabilities and provide a holistic consideration considering different aspects of circularity in the food sector.

In conclusion, the two research questions are:

RQ1: what are the possible circularity indicators to be applied in the food sector?

RQ2: how can companies orient themselves in their choice of indicators?

3.2 Creation of a framework through indicators collection and evaluation

The following paragraphs describe the methodology followed for addressing the first research question. Section 3.2 describes the process through which indicators were extracted starting from the analysis of the papers found in the literature (chapters 1 and 2). Section 4.1 exposes the results of the list of indicators identified. Section 3.3 presents criteria by which these indicators can be classified and clustered to make selection more accessible for decision makers, while the final picture obtained through all these analyses developed is reported in section 4.1.

The search for indicators for answering the first research question was carried out following well-defined and established methodology to achieve transparency, replicability and robustness of results. The aim of this section is providing insights about the process followed in order to develop the table of possible and useful indicators.

The section is structured on three paragraphs based on the criteria applied in the selection process: characteristics, goal and subject of the indicators.

3.2.1 Characteristics of the indicators

This first aspect considered to select the metrics concerns the characteristics it must have. These specifications are essential because they allow the decision-makers to understand and therefore interpret the indicator in order to generate knowledge about significant practises, using this information as a feedback loop to direct decision-making (P. D. Kravchenko M. 2021).

Indicators with measurable values were included, the data required to measure them need to be feasible to collect, reliable and up to date. Then, indicators have to aim at a reference value; a variable does not acquire significance or reveal information about changes in the status of a system if it does not point towards anything (a goal, an aim, a norm, a standard, or a benchmark) (Waas T. 2014). In this way, a reference scale can be developed, it can enable internal comparison (analyse the change over the years, in the same year but in different areas of the same company, ...) or external comparison (with other companies in the same sector, in different sectors, ...). Lastly, indicators need to have a unit of measurement.

Thus, these conditions exclude qualitative indicators, such as those assessed through ‘yes’ and ‘no’ grading.

3.2.2 Goals of the indicators

The second selection criterium adopted was based on the analysis of the purpose the indicators serve. As the literature review has already revealed, one of the major problems concerning the presence of countless indicators lies in the different nuances with which they are applied and studied. Two main categories have been identified: various authors present i) measures of circularity and ii) measures of sustainability of circular approaches. The difference between them lies in their goals: the former are drivers in decisions to achieve circularity since they directly impact a circular economy aspect, while the latter assess how well a strategy respects the achievement of sustainability, without providing information required for decisions in circularity aspects.

It was decided to focus only on pure circularity indicators as they have more gaps and problems in implementation. In order to select the proper indicators among all, a homologation process definition is still required for the necessary goal of robustness and clarity to be achieved. The criteria applied to select only this typology of indicators involve CE and SDG principles. Only indicators that met both inclusion criteria were selected.

First, for a parameter to be called a circular indicator, it must be related to at least one of the aspects derived from circular economy principles, which are i) design out waste and pollution, ii) keep products and materials in use, iii) regenerate natural systems (Ellen MacArthur Foundation, 2015). In practical terms, the indicators are taken into consideration if they impact:

- Waste and pollution management: the indicator expresses either the quantity, quality, typology, costs associated to the waste of materials, products or parts and to emissions and source of pollution along the whole value chain of a product. The aim is reducing its value to preserve natural resources.
- Flow of resources: in each stage of a general supply chain, different resources are applied in order to create the final product, such as raw materials, energy, space usage. The value is included if it considers either the quantity, quality, composition, source, complexity, scarcity, durability, lifecycle analysis, values and costs of a resource. The aim is reducing and optimizing them.
- Efficiency and productivity: the value expresses the capability of a resource to pursue the two aspects just mentioned, improving its performance and achieve the best result.

The other inclusion criterion related to define the aim of indicator concerns the impact it has in achieving the SDGs affected by the Circular Economy. As presented in paragraph 1.2.1, Circular Economy impacts 12 SDG's out of 17. The metric was considered if it answered to the question "does this indicator measure an aspect that can influence the circularity (analysed with the principles just mentioned) of this SDG?". Consequently, indicators that impacted SDGs not related to the Circular Economy were excluded, since they do not make a relevant contribution to the achievement of circular models.

The result obtained is a set of indicators that express the various dimensions of the circular economy, and thus are useful to decision makers when the object of the decision is the choice of circular strategies to implement or assess, because they can be declined within the different stages of the decision-making process and provide support.

3.2.3 Subject of the indicators

Since the focus of this report is on agri-food sector, this last paragraph shows the criteria applied in order to select the indicators most useful within this specific industry. The outcome after this step is a final framework which includes the lists of possible indicators useful for decision makers to achieve circularity goals.

The relevant criteria were identified based on the characteristics of existing frameworks, presented in paragraphs 2.2.2 and 2.2.3. The emerged key aspects not only characterize the sector but are also critical points in the development of circular strategies. Among the models presented, EWF Nexus model (Jacob C. 2021) highlights energy, water and food as key aspects to focus on. Furthermore, Food Waste Hierarchy (Papargyropoulou E. 2014) provides specifics regards waste management options.

These models concentrate mainly on the organic properties of food products, but also packaging play a critical role since it can preserve good properties along the life cycle. So, a distinction was made between organic food products and packaging items when discussing this paragraph. This step was necessary because certain strategies take on a different meaning since inorganic product hasn't certain properties presented instead in an organic good, which differentiates the food sector from all other sectors in the market, bringing with it greater complexity.

Thus, for what concern organic dimension, 10 R strategies, as a development of CE principles, were coupled with the core elements of the sectors to select the most appropriate indicators. A defined methodology path is obtained to choose the most suitable metrics. Table 5 shows the comparison between Food Waste Hierarchy and EWF Nexus in order to highlight the correspondence dimensions with the 10 R strategies.

Table 5 - Levels of correspondence between 10 R strategies and Food Waste Hierarchy

10 R strategies	Food Waste Hierarchy	EWF Nexus
	(Prevention)	
Refuse		
Rethink		
Reduce		Energy Water
Reuse	Reuse/redistribution for human consumption Reuse for animal feed	
Repair		
Refurbish		
Remanufacture		
Repurpose		
Recycle	Recycle	Energy Water
Recovery	Recovery	
	(Disposal)	

As highlighted in Table 5, CE strategies were limited to four (Reduce, Reuse, Recycle, Recovery). These strategies are significant for the organic product category because they represent possible approaches that reflect and take into account product properties. The remaining one are excluded since they cannot be applied to products that are not subject to manufacturing processes.

So, 'Reduce' strategy, which aims at increase efficiency in product use or manufacture by consuming fewer natural resources (Morseletto P. 2020), is essential since food production requires in the first step of supply chain the usage of soil and other natural resources to produce goods. 'Re-use' has to focus on the amount of waste generated along the whole chain which is still in good condition and fulfils its original function. These quantities can be allocated for other people or for animal feed. 'Recycle' strategy aims at process materials such as energy and water, obtaining the same or lower quality to implement in the production and thus reduce again the waste. 'Recovery' instead focuses on the incineration of organic materials, which are a huge quantity, with energy recovery.

Regarding packaging products, the criteria used to select the indicators are related to all 10 R strategies, so it follows hand in hand with the criterion presented in the previous paragraph. The focus to select specific indicators for this category was specifically on particular aspects, such as product manufacturing requirements based on the product it has to contain, assembly and disassembly time and activities, and the amount and variety of material used.

The demarcation applied finds correspondence also in the butterfly model by Ellen MacArthur Foundation (2019): it is composed by cycles for the flow of a resource, divided into biological and technical typologies, which can be linked to organic products and packaging respectively. Therefore, the indicators related to agri-food follow the cycles and expressing resource flow management referred to biological side, so that come from nature and can be returned via composting or similar processes without negatively affecting the natural environment, or technical side, which are instead synthetic materials, designed to be reused with minimal energy and highest quality retention. Moreover, the butterfly model helps identify strategies and metrics to enhance and prolong the cycle time, extending the life of a product.

3.3 Classification and clustering

Once the indicators have been selected, they were all classified according to the most popular aspect found in literature in order to obtain and easy framework to use based on the needs of the company. Furthermore, all the indicators dealing with common topics have been clustered in different packages, in order to highlight the main fields explored by the indicators in the database. This chapter explains therefore how both classification (paragraph 3.3.1) and clustering (paragraph 3.3.2) were carried out.

3.3.1 Classification

The indicators classification has been performed according to some parameters chosen among those already described in section 1.5 of the Literature Review. In particular, all the metrics have been evaluated based on their impact on the Triple Bottom Line (Environmental, Social, Economic), the CE strategies of the agri-food sector (Reduce, Reuse, Recycle, Recover) and the level of analysis (nano, micro, meso, macro).

The governance aspect has been excluded from the Triple Bottom Line classification, given the scarce impact that the Circular Economy has on this area. Indeed, they refer to business management and behavior issues, such as heterogeneity of the Board of Directors, corruption, anti-competitive practices and transparency, that are not directly impacted by Circular Economy strategies. On the other hand, environmental and economic objectives are core concepts of Circular Economy (Sauve S. 2016) and most of the metrics collected from the literature are focused on these two pillars. Indicators belonging to the environmental dimension concerns the identification and management of organization's impacts on the natural ecosystems (Bell S. 2008, Sauve S. 2016). They typically capture aspects related to resource consumption (material, energy, water, land), use of chemical and harmful substances, waste generation and emissions to water, soil and air (Joung C.B. 2013). A number of interesting indicators from an environmental point of view but that do not directly affect the circularity of processes, such as level of noise, vibration and radiation, were excluded from the table. Economic indicators aim instead to measure the value creation of a company through the implementation of CE strategies, by monitoring its costs, revenues, efficiency and productivity (P. D. Kravchenko M. 2019). It’s worth noting that many indicators, especially those relating to resource consumption, are present in literature both in economic and environmental perspective. Indeed, in many cases the same indicator can be measured from an economic point of view or in terms of environmental impact, while substantially measuring the same thing.

Finally, because of the debate that has emerged on the inclusion of social aspects within the concept of circularity (L. A. Schröder P. 2020), it is necessary to clarify the perspective adopted for social indicators included in the table and the reasons behind it. Since Circular Economy aims at achieving Sustainable Development (Corona B. 2019, Geissdoerfer M. 2017, A. K. Schröder P. 2019), it has to include all the necessary perspectives required to pursue it adopting the holistic approach. Thus, including social aspect is required. But as mentioned in the Literature Review, many authors argue that in Circular Economy assessment the focus should be placed on the training and education of the stakeholders involved in the different activities along the whole supply chain (Kirchherr J. 2017, Moreau V. 2017). The aim should be to raise awareness among all actors so that they can adopt behaviours and take actions more aimed at achieving circularity of the products used and contribute actively to the achievement of sustainable development. Compared to social sustainable indicators, the focus shifts from inside the company to outside, involving all typologies of stakeholders throughout the supply chain, from suppliers to private consumers and communities. This approach takes on even more importance and meaning when contextualised within the specific food sector, which is not only based on a strong interaction of the various actors, but whose sustainable performance results are determined by the actors themselves. For these reasons, social indicators included in the table are focused on collaboration between different actors in the supply chain, local initiatives and stakeholder awareness about more sustainable consumption and production practices, leaving out all those indicators concerning health and safety of customers and employees, salaries, human rights and equality that are crucial for social sustainability but are not directly connected to the concept of circularity. Moreover, many indicators that in literature were classified only as environmental or economic, have been made socio-environmental and socio-economic in this table since they include a social awareness perspective.

Regarding the classification of food indicators based on the CE strategies, it was carried out in accordance with the definitions given in the previous chapter of Reduce, Reuse, Recycle and Recovery. On the other hand, the indicators concerning packaging have been classified based on the 10R strategies framework described in chapter x.

The last classification concerns the level of analysis, and therefore nano, micro, meso and macro following the framework proposed by De Oliveira et al. (2021). As explained in Section 1.5, nano indicators refer to single products or materials, micro level to the whole companies, the meso approach applies to a supply chain perspective and finally macro level refers to Circular Economy development in cities and regions. This classification looks at the level of analysis on which the impact of Circular

Economy practices can be measured. For example, several indicators focused on the use of resources and production plants have been classified as micro, and therefore at the enterprise level, as it may not be feasible to allocate those resources to individual products according to a nano level. On the contrary, for some indicators about the use of energy and natural resources and other economic indicators, it might be interesting to adopt a macro perspective in order to understand their trends at a regional, national or global level.

3.3.2 Clustering

While the classification described in the previous section refers to the impact that the indicators measure in terms of sustainability dimensions, CE strategies and level of analysis, clustering refers to the grouping into packages of indicators that deal with common topics and indicate the application field' s scope. The groups of indicators that emerged are air, water, soil, energy, material and resource consumption, waste, transportation, social, revenues, costs, efficiency and productivity.

Indicators belonging to the air group concern air pollution and measure the quantity of various emissions that are harmful to health and the environment. Water-related indicators are instead focused on pollution caused by the presence of hazardous substances, and they measure the way in which this fundamental resource for the agri-food sector is collected, purified, used, reduced, recycled and recovered. Following the logic of the Water-Food-Energy nexus, also the energy-related indicators have been clustered, and they mainly concern energy consumption, the nature of power sources (renewables, fuel, ...), energy efficiency and the power obtainable from recovery. Although they are not widespread in literature, a group of soil-related indicators has also been identified, focused on the use of land areas and the consumption of pesticides and fertilizers.

After having isolated these elements considered most relevant for the initial stage of agri-food sector, two groups of more generic but equally relevant indicators have been identified, which are material and resource consumption and waste. This distinction is based on the flow of materials considered in the calculation of the indicator: if the metric relates to an input flow for processing the product, then it will be referred to resource consumption; on the other hand, if the metric refers to an output material flow, then it will be considered waste. These indicators are relevant not only at the production stage, but they have a key role especially in the following phases. The stocking, transportation, retailing activities require materials to preserve the product and prevent it from expiring and no longer being consumable. These activities are consuming and require attention to optimize the process. So, the first group of indicators measures the consumption of different types of materials and resources in terms of their nature (virgin, recycled, renewable, hazardous, ...) and their potential in the implementation of CE strategies (reusability, recyclability, ...). The second cluster of indicators monitors instead the type of waste (liquid, solid, hazardous, ...), the origin (damaged products, production processes, service providers, ...) and once again the potential in the implementation of CE strategies.

Transport-related indicators are isolated since logistic activity is consuming in a developed supply chain such as the food supply chain, in terms of time, requirements, and therefore also costs. It measures the impact generated by the flow of materials required and the particular conditions, such as specific temperatures, dimensions, quality which must be satisfied for the transport of agri-food products and stocking.

Finally, all the social indicators have been grouped together, as well as those relating to specific revenues, costs and efficiency and productivity dimensions. Obviously some economic and social indicators are distributed also in the previous clusters, but the principal and more generic ones have been grouped here in order to make them more easily identifiable by the decision-maker in the indicator selection phase.

As already mentioned, a clear distinction was maintained between the indicators relating to the agri-food sector and those specific for packaging. This is due to the fact that they focus on two different sides of the butterfly model, respectively the organic and the technical one, and therefore the CE implementation strategies as well as the aspects to be monitored are quite different. For reasons of consistency, the same clusters have been isolated for both macro-groups of indicators, even if the specific metrics of packaging do not cover some aspects such as air, water and soil.

4 Results and Discussion

This chapter describes the results obtained through the application of methodologies exposed in sections 3.2, 4.1 and 3.3 in order to identify a selected number of useful indicators.

Section 4.1 reports the final framework obtained through the selection, classification and clustering processes.

Therefore, a data analysis has been performed on the dimensions presented. More precisely, category analysis was conducted in section 4.2, studying each category individually, as well as comparing it with the others, in order to identify recurring trends, particular and additional critical points. Instead, section 4.3 contains considerations and results of clustering process.

4.1 Final table - List of indicators

This section provides the results of the process described in sections 3.2 and 3.3. Table 6 presents the list of the 163 specific metrics related to the product and focused on circularity in food sectors which satisfy the criteria presented above. The last column of the table includes the articles associated to these metrics; it is possible to find in Appendix A the reference papers associated to the number in the column.

Table 6 – Complete list of circularity indicators (food and packaging)

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
		FOOD INDICATORS		
1	Greenhouse Gases from Energy Use [MM ton of CO_2 emission]	Amount of GHG emissions (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6 tons of CO_2 equivalent) from energy use during processing in million tons	Total CO_2 emissions from energy use in primary operations	14, 59, 61
2	Total Greenhouse Gas Emissions [kg or kg/PO]	Amount of GHG emissions from energy use during overall production process in million tons	Sum of all air emissions in the production process	14, 59, 61, 47, 65
3	Specific Greenhouse Gas Emissions [volume /unit of product]	Amount of emissions of specific substances per unit of product or in terms of Production Output (PO) in kg, items, etc…	Quantity of specific emissions per unit of product	14, 59, 63
4	Acidification Potential [kg SO_2 eq]	Acid deposition of acidifying contaminants on soil, groundwater, surface waters, biological organisms, ecosystems, and substances	$\frac{X_{AP(T)}}{X_{AP}}$ with X_{AP} = acidification potential in the local environment and $X_{AP(T)}$ =190 μg m^{-3}, set by EPA for the ambient air quality	54

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
5	Aquatic acidification [kg SO_2 eq]	Ambient air quality concentrations of oxides of nitrogen and sulfur to potential surface water acid neutralizing capacity (ANC) within a NAAQS framework	$\sum AP_i \; x \; m_i$ with APi = Acidification Potential for substance 'i' emitted to the air and m_i = emission of substance 'i' to air, water or soil	54
6	CFC Emissions [tons of CFC-11/year]	Amount of CFC emissions during manufacturing in tons of CFC-11 per year	Total CFC emissions per year	54, 59
7	Photochemical Ozone Formation Mass Fraction [dimensionless]	Amount of photochemical ozone formation (smog) potential mass fraction to the total mass of products manufactured	Total mass of ethylene equivalents/Total mass of products	14, 59
8	Photochemical oxidant creation potential [kg C_2H_4 eq]	Quantifies the relative abilities of volatile organic compounds (VOCs) to produce ground level ozone	$\frac{\text{Ozone increment with the ith VOC}}{\text{ozone increment with ethene}} \; x \; 100$	54
9	Fuel Emissions-Exhaust in Logistical Waste [kg gas/product]	Amount of fuel emissions-exhaust due to logistical waste per product manufactured during the production process	Fuel emissions-exhaust per product	14, 59
10	Volatile Organic Compounds [mass units]	Quantity of VOCs emissions during the any life cycle stage	Quantity of VOCs emissions in any life cycle stage per production output	14, 59, 66
11	Persistent Organic Pollutants [mass units]	Quantity of POPs emissions during the any life cycle stage, including the contents of dioxins and furans in the air that are relevant to the EuP, but no emissions to water	Quantity of POPs emissions in any life cycle stage	14, 59
12	Polycyclic aromatic hydrocarbons [mass units in Ni-eq]	Quantity of PAHs emissions during the any life cycle stage	Quantity of PAHs emissions in any life cycle stage	14, 59
13	Particulate Matter [mass units]	Quantity of PM emissions during the any life cycle stage	Quantity of PM emissions in any life cycle stage	54, 59
14	Heavy metal emissions to water [tons/year]	Total amount of heavy metal (arsenic, cadmium, chromium, lead, and mercury) emissions to water in tons per year	Total amount of heavy metal emissions to water per year	14, 54, 59
15	Hazardous Sludge Volume [volume units]	Generation of hazardous sludge volume during the production process	Amount of hazardous sludge volume generated	14, 59
16	Total Water Consumption [m^3]	Absolute volume of all water used in the production process or related activities	Volume of all water used in the production process	14, 47, 54, 59, 65, 66
17	Specific Water Consumption [m^3/UP (Unit of Production)]	Volume of all water used in the process to the output; it can include reused water	Water consumption volume/Production Output Production output = unit of product, part, materials	14, 59, 63, 66
18	Reused and recycled water ratio [%]	Amount of water reused or recycled in the (production) process to the total amount of water used	$\frac{\sum \text{water reused/recycled in the production process}}{\sum \text{water consumed in the production process}} \; x \; 100$	14, 59, 62, 65, 66
19	Product Fresh Water Use [litres/product]	Amount of fresh water used per good produced, not including reused water in production	Amount of fresh water used per good produced	14, 54, 59
20	Pollution Mass Concentration in Liquid Waste [kg/m^3]	Mass of pollutants, such as Phosphorus, Nitrogen, Lead, etc, in relation of the total liquid waste volume	Mass of pollutants/Liquid waste volume	14, 59
21	Wastewater Treatment Rate [%]	Quantity of treated wastewater to the total generation of wastewater during the production process	Treated wastewater/Wastewater generation	14, 54, 59
22	Biochemical Oxygen Demand [ppm in effluent or kg/t]	Amount of BOD discharged in ppm in effluent or kg/t. BOD can be used as a gauge of the effectiveness of wastewater treatment	$\frac{\sum \text{(annual consumption of chem i .BOD percentage i)}}{\text{annual production}}$	14, 59, 63
23	Chemical Oxygen Demand	Amount of COD discharged in ppm in effluent or kg/t. COD is the total	$\frac{\sum \text{(annual consumption of chem i .COD percentage i)}}{\text{annual production}}$	14, 59, 63

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
	[ppm in effluent or kg/t]	measurement of all chemicals (organics & in-organics) in the water or waste water		
24	Green Water Footprint [m^3]	Volume of rainwater consumed during the production process	Green Water Evaporation + Green Water Incorporation	19, 54
25	Grey Water Footprint [m^4]	The volume of water needed to dilute pollutants until water quality standards are restored	$\frac{L}{cmsx - cnat}$ L = pollutant load in mass/time; cmsx = maximum acceptable concentration of ambient water quality standard; cnat = natural concentration in the receiving water body	19, 54
26	Blue Water Footprint [m^5]	Consumption of virgin water resources (surface and groundwater, i.e., lakes, rivers and aquifers) along the supply chain or of a product.	Blue Water Evaporation + Blue Water Incorporation + Lost Return Flow	19, 54
27	Water Circularity Index [%]	Measure the level of restorative flow at product and firm level with the focus on water use.	$1 - \frac{\text{Bluewater} + \text{wastewater}}{2 \text{ x total water flow}}$ with wastewater = volume of polluted and discharged water; total water flow =volume of water used for plant operations	19, 54
28	Water Scarcity Index [m^3]	Ratio of water consumed to available water	$\frac{\text{Bluewater}}{\text{Water available}}$	54
29	Water exploitation index [%]	Sustainability of the water abstraction process by considering the availability of the water resource	$\frac{\text{Abstraction} - \text{Returns}}{\text{Renewable water resources} - \text{Environmental flow}} x\ 100$	54
30	Level of water stress [%]	Ratio of available water resources to withdrawn resources	$\frac{\text{WW}}{\text{TRWR} - \text{EFR}} x\ 100$ WW = total freshwater withdrawn TRWR = total renewable water resource EFR = environmental flow requirements	54
31	Eutrophication Mass Fraction [dimensionless]	Eutrophication mass fraction to the total mass of products manufactured. Excessive amounts of organic pollutants can lead to eutrophication	$\frac{\text{Total mass of phosphate equivalents}}{\text{Total mass of products}}$	49
32	Eutrophication potential [kg phosphate eq]	Increase in aquatic plants due to excessive release of nutrients from fertilisation (e.g. nitrogen and phosphorus)	$\sum \text{Epi x mi}$ EPi = EUP for substance 'i' emitted to air, water or oil	54
33	Pesticide use [t/t]	Amount of pesticide use in raw materials to the production output of a product	Amount of pesticide use/production output	14, 59
34	Fertilizer consumption [kg/area]	Amount of plant nutrients (nitrogenous, potash, phosphate) used per unit of arable land	$\frac{\text{Fertilizer}}{\text{Arable land}}$	54
35	Total land area used for production [area units]	Total land area used for production & other operation purposes including land use for crop cultivation (crop for food, bio-energy production, wood)	Total land area used for production purposes	14, 54, 59, 63
36	Total area Equipped for irrigation [%]	Area with direct access to water supplies	$\frac{\text{Area equipped for irrigation}}{\text{Total agriculture area}} x\ 100$	54
37	Proportion of land that is degraded over total land area [%]	Land that suffers a loss of productivity (biological or economic)	$\frac{\text{A(degraded)}_n}{\text{A(total)}_n}$ $\text{A(degraded)}_n = \text{A(persistent)}_n + \text{A(recent)}_n + \text{A(improved)}_n$	54
38	Phosphorus balance on agricultural land [kg/area]	Degree of presence of the nutrient in the soil, introduced as fertilizer, defines the impact of agricultural practices on soil quality	$\frac{\text{Inputs of phosphorus} - \text{phosphorus removed}}{\text{Total arable land}}$	54
39	Nitrogen balance on agricultural land [kg/area]	Degree of presence of the nutrient in the soil, introduced as fertilizer, defines the impact of agricultural practices on soil quality	$\frac{\text{Inputs of nitrogen} - \text{nitrogen removed}}{\text{Total arable land}}$	54
40	Average carbon content in the topsoil [% of weight/product]	Soil quality measured by the presence of carbon	Average carbon content in the topsoil as % in weight	54
41	Total Energy Consumption in primary processing [kWh]	Total energy consumption of the processing (including cooling process, air conditioning and purification processes)	Total energy consumed for primary manufacturing	14, 39, 59, 62, 65, 66

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
42	Specific Energy Consumption in the processing [kWh/UP]	Total energy consumption of the processing per production output	$\frac{\text{Total energy consumed}}{\text{Production Output}}$	14, 59, 63, 65
43	Specific Energy Consumption in operations [kWh/UP]	Total energy consumption of the repair process per process output (repaired product)	$\frac{\text{Total energy consumed}}{\text{Operation Output}}$	14
44	Renewable Energy Fraction [dimensionless]	Quantity of renewable energy use to the total amount of energy used in the (production) process	$\frac{\text{Renewable energy consumption}}{\text{Total energy consumption}}$	14, 54, 59, 63, 65
45	EE Energy Efficiency of a production process [%]	It is related to the energy efficiency of a part of the production process type n (e.g. plastic injection)	$\frac{W}{E}$ W =real work performed by this unit E = energy consumption of doing the work.	14, 59, 66
46	Recovery of energy by using waste [J]	Amount of energy produced by waste recovery from of animal fat/processed animal or tonnes of organic waste/processed animal	EEp = w * Q * CPee with Q = productivity, w = quantity of waste, CPEE = other energy parameters, the treated waste is converted into electric energy	54
47	Energy self-sufficiency [unit]	Capability of the system to produce an amount of energy necessary for its operation	$\frac{\text{EEp}}{\text{EEr}} = \frac{\text{w} * \text{Q} * \text{CPeeP}}{\text{EEr}}$ EEp = energy produced in the supply chain by using waste EEr = energy required where the waste is produced	54
48	Energy generated with process streams [energy units]	Amount of energy generated (energy loss) from process streams	Quantity of the energy generated with by-products or process streams	14, 59
49	Biomass energy production [%]	Bioenergy produced out of total renewable energy produced	$\frac{\text{Bioenergy produced}}{\text{Total renewable energy produced}} x\ 100$	54
50	Biomass energy per Product [J/product]	Quantity of biomass energy used to manufacture the product	Biomass energy used to manufacture the product	14, 59
51	Natural Gas consumption [MJ/product]	Amount of natural gas used to process the product	Natural gas used to produce the product	14, 59
52	Electricity Consumption [kWh/product]	Amount of electricity used to process the product	Electricity used to produce the product	14, 59, 66
53	LPG consumption per product [litres/product]	Amount of LPG (Liquefied Petroleum Gas) used to process the product	LPG used to produce the product	14, 59
54	Fuel consumption per product [litres/product]	Amount of fuel used to process the product, including petrol and diesel consumption for transportation	Fuel used to produce the product	14, 59
55	Wood fuel production [tons]	Fuelwood or firewood (in log, brushwood, pellet or chip form) obtained from forests or isolated trees	Tonnes of wood fuel production	54
56	Primary Embodied Energy of material [MJ/kg]	Investigate the EE index of raw materials that are used in product	Energy necessary to extract and produce one kg of the raw material type *m*	14, 59
57	Recycled Embodied Energy [MJ/kg]	Investigate the EE index of raw materials that are used in your product	Energy necessary to recycle and produce one kg of the recycled material type *m*	14
58	Volume of chemicals and solvents [volume]	Volume of chemicals and solvents used which can pose risk to human health and environment	Volume of chemicals and solvents used in manufacturing process	14
59	Lubricant and Coolant Fluids [volume]	Amount of lubricants and coolants required by the machine tool, or product	Type of lubricants and coolants, and their consumption in manufacturing and use stages	14, 59
60	Total oil consumption (n-e) [litres]	Amount of oil consumed in production processes (not for energy purpose)	Amount of oil consumed in the production process	14
61	Total Material Consumption [kg]	Quantity of absolute mass of material input to process the product	Total material input mass in processing	14, 59, 61, 65

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
62	Specific Material Consumption [kg/UP]	Quantity of mass of material input per production output. It can be amount of materials used to process a product or to substitute virgin material	$\frac{\text{Total material input}}{\text{Production Output}}$	14,29, 59
63	Fraction of Renewable Raw Materials [dimensionless]	Amount of renewable raw materials used to the total mass input in the operational system, as material of plant, animal, or microbial biomass	$\frac{\text{Renewable raw material input}}{\text{Total material input}}$	14, 59, 63
64	Sustainability-certified materials product [%]	Quantity of sustainability-certified materials/substances/ingredients in material use for product processing	$\frac{\text{Total sustainability} - \text{certified materials}}{\text{Total materials used in product manufacturing}}\ x\ 100$	14
65	Amount of Restricted Materials (REACH) [mass/product]	Mass of all restricted materials (AZO dyes, DMF, PAHs, Phthalates, PFOS, the nickel release, etc…) used in a product, which can pose risk to human health or the environment	$\frac{\text{Mass of all restricted materials}}{\text{Product}}$	14, 59
66	Hazardous materials used by service providers [mass OR volume]	Amount of hazardous substances used by service providers (also contracted)	Amount of hazardous substances used by service providers	14, 59
67	Materials used during after-sales servicing [mass OR volume]	Amount of materials used during servicing of products	Quantity of materials used during after-sales servicing of products	14, 59
68	Input of virgin material [mass]	Quantity of the inputs that are coming from virgin materials in relation to the rest of materials coming from recycled or reused materials and components	M x (1 - FR - FU) M = Mass of a product; FR/FU = Fraction of mass of a product's feedstock from recycled/reused sources	14, 19, 39, 47, 59, 66
69	Reused materials [%]	Rate of reused materials to the total material consumption in processing	$\frac{\text{Reused materials}}{\text{Total material consumption in processing}}$	14, 59, 62
70	Recycled defects [%]	Rate of recycled defective products to the total number of defective products	$\frac{\text{Recycled materials}}{\text{Total number of defective products}}$	14, 59
71	Amount of recycled scrap [%/product]	Rate of scrap recycled in the production process per product produced	$\frac{\text{Scrap recycled in the production process}}{\text{product manufactured}}$	14, 59
72	Total Recyclable Material in Processing [mass units/month]	Amount of recyclable materials used in processing per period of time	Mass of recyclable material processed per period of time	14, 59
73	Recycled Material Fraction [dimensionless]	Amount of recycled material used to the total mass input in the manufacturing system. It can also be measured as an absolute indicator, reflecting the amount of recycled materials used in a period of time	$\frac{\text{Recycled material input}}{\text{Total material input}}$	14, 35, 59, 63
74	Additional material to create recycled feedstock [kg]	Amount of additional material (material can be waste or leftover material) needed to create recycled feedstock to be used for product processing	$\frac{\text{M}}{\text{Ef}}\ x\ [(1 - Ef)x\ Fr]$ M = mass of the finished product; Ef = efficiency of the recycling process used to produce recycled feedstock; Fr = fraction of the feedstock derived from recycled sources to be used in a product	14, 47
75	Nutrient circularity indicators (carbon, nitrogen and phosphorus) [mass]	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	$\frac{\sum\sum RiJk\ x\ nrij\ x\ nPik}{wi}$ wi= amount of component i present in the waste stream RiJk= amount of component i that enters the recycling process j nrij = efficiency of the recycling process j for component inPik = efficiency of the production process k at transforming or incorporating the recovered component i into a product that will deliver a service in the consumption subsystem	54
76	Product Solid Waste Fraction [% of weight/product]	The product is treated as solid waste if there is no EoL management option other than landfilling or incineration available	$\frac{\text{Mass of non} - \text{recovered parts of the product}}{\text{Total mass of product}}$	14, 54, 59
77	Waste generated in the recycling process [kg]	Amount of waste generated in the recycling process. The value can be low due to smaller fraction of the product being collected for	M x Cr x (1 - Ec) M = mass of the finished product; Ec = efficiency of the recycling process used for	14, 47

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
		recycling, or it may also indicate that the rest of the fraction of the product is destined to landfilling	recycling the product at the end of its use phase; Cr = fraction of the mass of the product being collected for recycling at the end of its use phase.	
78	Rate of Damaged Products [%]	Number of damaged products to the number of processed goods. Decrease this rate reduce solid waste generation, and wasted materials and energy	$\frac{\text{Number of damaged products}}{\text{Total number of processed product}}$	14, 59
79	Total Solid Waste Mass [kg]	Absolute mass of solid waste generated in the processing or operation process	Mass of solid waste generated	14, 65
80	Specific Solid Waste Mass per type of Waste [kg/UP]	This indicator measures the absolute mass of solid waste generated in the manufacturing process per type to production output	$\frac{\text{Mass of specific type of solid waste}}{\text{Production output}}$	14, 59
81	Waste generated by service providers [kg]	Amount of waste generated by service providers. It can be also measured for different types of waste generated	Amount of waste generated by service providers	14, 59
82	Waste controlled by permits [mass or volume units]	Amount of waste generated in the processing stage controlled by permits. Permits are normally obtained for business in areas as energy activities, metals production and processing; mineral activities, activities involving the use of solvents.	Quantity of waste controlled by permits	14, 59
83	Landfill Waste per Product [kg/product]	Quantity of material sent to landfill per unit of product. Aim to eliminate materials sent to landfill.	Quantity of material sent to landfill per unit of product	14, 59
84	Recycled Solid Waste Mass Fraction [dimensionless]	Amount of recycled solid waste mass to the total amount of solid waste generated	$\frac{\text{Recycled solid waste mass}}{\text{Total mass of solid waste generated}}$	14, 59
85	Total Solid Waste Mass for Disposal [kg]	Amount of solid waste mass generated for disposal, and can also be measured in a certain period of time	Non-recovered solid waste mass in absolute terms	14, 45, 59
86	Hazardous Solid Waste Mass Fraction [dimensionless]	Relative quantity of hazardous solid waste produced by the company to the total amount of waste generated	$\frac{\text{Mass of hazardous solid waste}}{\text{Total mass of solid waste}}$	14, 45, 59
87	Hazardous Solid Waste Mass [kg]	Total amount of hazardous solid waste produced by the company	Mass of hazardous solid waste	14, 45, 59, 66
88	Total volume of Liquid Waste [m^3]	Total volume of liquid waste produced in a process in a period of time	Volume	14, 59, 65
89	Specific Liquid Waste Volume [m^3/UP]	Quantity of liquid waste per unit of production or process output	$\frac{\text{Total volume of liquid waste}}{\text{Production Output}}$	14, 59
90	Polluted Liquid Waste volume [m^3]	Total volume of polluted liquid effluents produced by the company. Measuring this indicator gives a good understanding of the efficiency of the liquid waste treatment in manufacturing process.	Volume	14, 59
91	Waste converted to Reusable Material [mass or volume /year]	Amount of waste generated by the production process converted to reusable material per year	Quantity of waste converted to reusable material per year	14, 59
92	Temperature Changes throughout supply chain, consumer use and disposal [ºC, ºF, K, ...]	Temperature changes during the product's life cycle, considering: Sourcing and production, Retail, Logistics and warehousing, Consumer Use and End-of-Life. Monitoring this indicator helps optimize energy use throughout supply chain	Temperature changes	14, 59
93	Freight deliveries by mode of transportation [freight deliveries/mode of transportation/day]	Number of freight deliveries by mode of transportation per day. As different modes of transport differ in their efficiency, this indicator aims to measure the proportion of transport in the whole supply chain of transport means	Quantity of the number of freight deliveries by mode of transportation per day	14, 59

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
94	Load mode of transport [%]	Amount of space capacity of transport is used, in percentage, in terms of area, volume and weight	% Full (area, volume, weight)	14, 59
95	Intensity of transportation [l/ t.km]	Measure of improvement in the efficiency of the freight transportation in terms of energy consumption	$\frac{\text{Energy intensity}}{\text{activity}}$	14, 59
96	Vehicles in fleet with technology [number]	Amount of vehicles in fleet with pollution abatement technology. Increase number of vehicles in fleet with pollution abatement technology	Total number of vehicles in fleet with pollution abatement technology	14, 59
97	Transportation Distance for production materials [km/product]	Distance from source in kilometres to get materials for production	$\frac{\text{Distance from source of raw materials}}{\text{product}}$	14, 59
98	Number of campaigns on responsible consumption [number]	Customers who actively participate in campaigns for more responsible consumption are more likely to change their behaviour and adopt novel products and solutions	Number of campaigns on responsible consumption	14, 59
99	Availability of customer support option [%]	Customer support can provide valuable information to the customer about proper product use (for example availability of recycling or recovery centre etc)	$\frac{\text{Number of satisfied support requests}}{\text{Number of total support requests}}\ x\ 100$	36
100	Contribution to local initiatives [dimensionless]	Percentage of operating income dedicated to social contribution	$\frac{\text{Contributions to the community}}{\text{Total revenues for the reporting period}}$	14, 65, 66
101	Purchase of locally produced and offered goods and services [dimensionless]	Amount of goods that a company has purchased locally	$\frac{\text{Mass of locally purchased products(goods)}}{\text{Total output mass of products produced}}$	14, 66
102	Products consumed locally [dimensionless]	Fraction of products that are planned to be sold for local market	$\frac{\text{Mass of locally consumed products(goods)}}{\text{Total output mass of products}}$	14, 65
103	Number of joint sustainability-oriented initiatives [number]	Joint initiatives in supply chain towards sustainability creates a robust knowledge sharing and commitment base	Number of joint sustainability-oriented initiatives	36
104	Suppliers without environmental standards [%]	Number of suppliers against environmental standards to analyse the supply chain and managing the level of supplier commitment to environmental procedures	$\frac{\text{Number of suppliers without environmental standards}}{\text{Total number of suppliers}}$	36, 65
105	Suppliers from the local area [%]	Number of suppliers that are from the local area or/and easily reachable	$\frac{\text{Number of suppliers from the local area}}{\text{Total number of suppliers}}$	36
106	Suppliers that have completed hazardous substances information [%]	Number of suppliers that have completed hazardous substances information. This accounting helps managing the level of supplier commitment to account and reduce hazardous/toxic material utilization	Percentage of suppliers that have completed hazardous substances information	36
107	Suppliers with EMS [number]	Number of suppliers with either certified or non-certified established EMS (Environmental Management System)	Number of suppliers with EMS	36, 59
108	Revenues from reused/repurposed products [EUR]	Amount of income generated by the sale of reused goods/products. Extend product's use cycles by offering reused products and goods for sale.	Number of reused/repurposed products type j sold *x* the unit sale price for reused product type j	14, 64
109	Revenues from reusable and recyclable parts [EUR]	Amount of income generated by the sale of reusable and recyclable parts to a third party. The revenues are sales from the four classes of components, such as good and poor-quality reusable parts and good and poor quality recyclable parts	$\sum(gri\ x\ Gr) + \sum(g'si\ x\ G'r) + \sum(pri\ x\ Pr) + \sum(p'si\ x\ P'r)$ Gr/Pr = number of good/poor quality reusable parts, G'r/P'r = number of good/poor quality recyclable parts, gri/pri = price of good/poor quality reusable parts and g'si/p'si = price of good/poor quality recyclable parts i	14
110	Revenues from eco-products [EUR]	Amount of income generated by the sale of goods/products labelled as eco-products by EU ecolabel, the Nordic swan, FSC, etc…	Number of eco-labelled product type *ep* produced and sold x the unit sale price for eco-labelled product type *ep*	14

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
111	Revenue fraction of eco-products [dimensionless]	Amount of income generated by the sale of eco-labelled products to the total amount of income from all products sold.	$\frac{\text{Revenues from sale of eco} - \text{products}}{\text{Total revenue}}$	14
112	Total energy costs [EUR]	Cost of energy used for primary production and auxiliary processes	Total amount of energy purchased (kWh) *x* price for 1kWh of energy	14, 62
113	Energy cost per unit of product [EUR/UP]	Cost of energy type *e* associated with a production of a product	Total cost for energy type *e* consumed in machine operation/total number of product units made	29, 62, 64
114	Energy cost fraction in production [dimensionless]	Fraction of the costs associated with purchasing of energy type *e* for primary production	$\frac{\text{Total energy costs}}{\text{Production costs}}$	14, 54
115	Material cost per unit of product [EUR/UP]	Cost of materials type j associated with a production of a product	$\frac{\text{Total cost of consumables (materials of type } j\text{)}}{\text{Production output}}$	14
116	Total material costs [EUR]	Cost of all materials associated with a production of a product	Total amount of material type *j* consumed (m^3 or kg) *x* price for m^3 (or kg) of material type *j*	14, 39, 62
117	Total water costs [EUR]	Costs associated with purchasing of water for production and auxiliary processes	Total amount of water purchased (m^3) *x* price for m^3 of water	14, 39, 62
118	Water cost fraction [dimensionless]	Fraction of the costs associated with purchasing of water for production and auxiliary processes	$\frac{\text{Total water costs}}{\text{Production costs}}$	14
119	Water cost per unit of product [EUR/UP]	Cost of water associated with a production of a product	$\frac{\text{Total cost for water consumed in machine operation}}{\text{Production output}}$	14
120	Number and cost of damages in processing [EUR/UP]	Number and cost associated with damaged in processing. Attempt to reduce this indicator's value to reduce the solid waste generation, and wasted materials and energy	Cost of defects in manufacture *x* number of damages	14, 64
121	Cost of disposal [EUR/UP]	Costs associated with goods disposal. The number of goods sent to disposal include the non-demanded and functionally damaged goods	Number of disposed items of different types *x* unit cost of disposal	29
122	Solid waste cost fraction [dimensionless]	Fraction of total costs incurred by the company from disposing solid waste in total production costs	$\frac{\text{Total costs of solid waste disposal}}{\text{Total production costs}}$	29
123	Scrap cost [EUR/UP or EUR/product]	The amount of scrap that is generated from the operational processes is a good indication of processing process efficiency and quality	$\frac{\text{Total cost of scrapped material}}{\text{Production output}}$	29
124	Total liquid waste costs [EUR]	Costs incurred by the company from disposing liquid waste	Total volume of liquid waste type *lw* to be disposed (m^3) *x* cost of liquid waste *lw* handling (EUR/m^3)	14
125	Liquid waste cost fraction [dimensionless]	Fraction of total costs incurred by the company from disposing liquid waste in total production costs	$\frac{\text{Total costs of solid waste disposal}}{\text{Total production costs t}}$	14
126	Fertilizers Manufactured value [EUR/product]	Economic value of the Fertilizers Manufactured per unit	$\frac{\text{Economic value of fertilizers manufactured}}{\text{Mass of fertilizers manufactured}}$	54
127	Organic fertilisers value [EUR/product]	Economic value of the Organic fertilisers per unit	$\frac{\text{Economic value of organic fertilizers}}{\text{Mass of organic fertilizer}}$	54
128	Pesticides value [EUR/product]	Economic value of the pesticides	$\frac{\text{Economic value of pesticides}}{\text{Mass of pesticides}}$	54
129	Costs of purifying air [dimensionless]	Costs incurred for running an air purification system (this can include energy costs)	$\frac{\text{Air purifying cost}}{\text{Total production costs}}$	14
130	Cost of recycling [EUR]	Recycling cost is defined as the amount of money to invest to remove targeted parts and materials	Σ [((i x MV m - OC i) x Wi) - (RT i x f x L)] i = number of parts of type i; Wi = weight of parts of type i; MVm = mass of material value of parts; RTi = time necessary to remove one type i part; L = hourly wage ; OCi = opportunity cost corresponds to the revenue the dismantler would make by selling the parts to the shredder; f = disassembly depth factor	14, 19
131	Traditional supply chain cost [EUR]	Cost produced as a result of a usual operation in the supply chain. It includes all costs accruable in ensuring that products get to the end customer	Delivery cost + inventory cost + information sharing cost + ordering cost	14
132	Transportation cost 1 [EUR]	Transportation cost from facility to disposal site. Landfilling shall be the least preferred option	$\frac{\text{Transported distance}}{\text{Fuel consumption}}\ x \text{ cost of fuel}$	14, 59, 64

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
133	Transportation cost 2 [EUR]	Transportation cost in processing stage (for example, for product packaging)	$\frac{\text{Transported distance}}{\text{Fuel consumption}}\ x$ cost of fuel	14, 59
134	Transportation cost 3 [EUR]	Transportation cost from facility to outside recycling plant	Number of items sent to the outside recycler x the transportation cost per unit from the facility to the outside recycler	14
135	Transportation cost 4 [EUR]	Transportation cost from facility to storage location (for example, to be stored for further collection to be recycled or disposed)	Number of items sent to storage x transportation cost per unit from the facility to the storage location.	14
136	Fuel consumption during distribution [EUR/product]	Cost associated with fuel consumption during product distribution	$\frac{\frac{\text{Transported distance}}{\text{Fuel consumption}}\ x\ \text{cost of fuel}}{\text{quantity of products transported}}$	14
137	Processing cost per unit [EUR]	Expenses related to the operation of equipment to produce a unit of product	$\frac{\text{Total fixed costs} + \text{Total variable costs}}{\text{Production output}}$	14
138	Cost of user education on use and post-use opportunities [EUR]	Cost of investments in user education to equip customers with the knowledge & skills needed to make the most out of its product at any stage of its operation and the end of life	Total amount of money spent on user education	14, 64
139	Cost of supplier education and training [EUR]	Cost of investments in suppliers' education and training to equip/enrich suppliers with the knowledge & skills in relation to innovative projects	Total amount of money spent on supplier education	14
140	Employee to customer ratio [ratio]	Service quality and employee efficiency in service provision/delivery	$\frac{\text{Number of employees in service delivery}}{\text{number of customers}}$	14
141	Overall equipment effectiveness [%]	This indicator measures the effectiveness of equipment in manufacturing a product identifying the percentage of manufacturing time that is truly productive	OEE = Availability x Performance x Quality; Availability= Run Time / Planned Production Time, Performance = Net Run Time / Run Time, Quality = Fully Productive Time / Net Run Time	14
142	Livestock production index [%]	Amount of meat and milk production and dairy products	$\frac{\text{Livestock production during year n}}{\text{Livestock production during year n} - 1}\ x\ 100$	54
143	Food production index [%]	Quantity of food crops that are edible and have nutrients	$\frac{\text{Food production during year n}}{\text{Food production during year n} - 1}\ x\ 100$	54
144	Crop production index [%]	Annual agricultural production as a function of a reference period	$\frac{\text{Crop production during year n}}{\text{Crop production during year n} - 1}\ x\ 100$	54
145	Energy productivity [EUR/Watts]	Ratio of the amount of economic output that is produced per unit of gross energy available	$\frac{\text{Total economic output}}{\text{Energy consumed}}$ Total economic output = revenues, GDP	29
146	Water Productivity [EUR/m^3]	Economic value generated by cubic metres of the total annual freshwater abstraction (in million m^3)	$\frac{\text{Total economic output}}{\text{Annual freshwater abstraction}}$	19, 29
147	Eco-cost Value Ratio [dimensionless]	Evaluate the potential environmental weakness linked to business models and to offer a new model on which giving useful information based on costs, eco-costs and market value	$\frac{(\text{Pollution} + \text{material} + \text{energy})\ \text{prevention costs}}{\text{Market value of the products delivered}}$	31, 35, 49
148	Value-based Resource Efficiency Indicator VRE [dimensionless]	Economic value of the resources	$\frac{\text{Value added}}{\text{Value of inputs, except for labour}}$	35, 41, 49
149	Resource Productivity Indicator [GDP per unit of resources]	Resource indicator through the measurement of the GDP output per unit of consumed resources.	$\frac{\text{Value added in production chain}}{\text{Inputs into the industrial system}}$	35, 54
150	Reuse benefit/cost ratio [dimensionless, >1]	This indicator shows how economically beneficial is to offer used goods. The benefit to cost ratio (BCR) must be greater than or equal to 1, i.e. B/C > 1, where B is the benefit and C is the cost of each alternative	$\frac{\text{Bresale}}{\text{Ccoll} + \text{Ctrans} + \text{Crefurb}}$ Bresale = resale value of the product Ccoll = collection costs; Ctrans = transportation costs; Crefurb =refurbishing costs (inspection, cleaning, packaging, etc...)	29, 31
151	Recycling benefit/cost ratio [dimensionless, >1]	This indicator shows how economically beneficial is to offer recycled materials for sale. The benefit to cost ratio (BCR) must be greater than or equal to 1, i.e. B/C > 1	$\frac{\text{Bweight x Bvalue}}{\text{Ccollection} + \text{Ctrans} + \text{Csep} + \text{Cshred}}$ Bweight = weight of the recovered material, Bvalue = market value of the material, Ccoll = collection costs, Ctrans = transportation costs, Csep = separation costs, Cshred = shredding costs	29, 31

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
152	Reuse index IEOL-Ru [dimensionless]	Possibility of a given component being reused in similar products. This EoL scenario is possible only when the component's lifetime is longer than the lifetime of the product itself	$\frac{V_{Re} + V_{Mat} + V_{Man} - C_{RL} - C_{Sd} - C_{C}}{V_{Re} + V_{Mat} + V_{Man}}$ VRe = value of reused materials VMat = no virgin material used to produce the goods VMan = no processing operations to build up the parts CRL = Reverse supply chain; CSd = Selective disassembly operations; CC = Cleaning operations	19, 35, 50
153	Recycling index IEOL-Rc [dimensionless]	Comparison between the production costs for virgin materials and the revenues coming from the recycling process. It establishes the real effective opportunity in terms of energy and cost reduction.	$\frac{V_{Re} + V_{En} - C_{RL} - C_{Dd} - C_{C}}{V_{Rc} + V_{En}}$ VRc = value of recycled materials VEn = energy saved by not producing virgin material	19, 35, 50
154	Incineration Index (with energy recovery) IEOL-Inc [dimensionless]	It establishes whether particular combinations of materials can be directly incinerated for energy production.	$\frac{V_{EInc} - C_{RL} - C_{Dd}}{V_{EInc}}$ VEInc = energy gained from combustion	19, 35, 50
155	Circular Economy Index CEI [dimensionless]	It aims at introducing the economic value of the materials embedded in products as the property to be measured and accounted. It is related to a wide range of strategic, economic, social and environmental aspects of recycling.	$\frac{\text{Material value due to recycling products}}{\text{Material value needed for reproducing end of life product}}$	31, 35, 41
156	Recycling Efficiency [%]	Quantifies how efficient the recycling processes used to produce recycled input and to recycle material after use are. Some materials require much less energy to be recycled compared to the original manufacturing	The value will depend on material(s); the quantity of material(s) involved; the recycling preparation process; Values for recycling efficiency	31, 35, 47
157	Linear Flow Index LFI [number]	It measures the proportion of material flowing linearly, that is, from virgin materials and up to unrecoverable waste.	$\frac{V + M}{2M + \frac{Wf - Wc}{2}}$ V + M = amount of material flowing in a linear fashion 2M + (Wf - Wc)/2 = amounts of material flowing in a linear and a restorative fashion (or total mass flow, for short)	29, 39
158	Material Reutilisation Score [%]	Calculation that combines the fraction of recycled or rapidly renewable content in a product with the fraction of material in a product that is recyclable, biodegradable or compostable.	Weighted average of intrinsic recyclability of the product and the % recovered content	16
159	Longevity Indicator [time units]	Assessment of the average life of product and material utilization. It shows the period of time for which a material is maintained in the production process. Through this retention the maximization of resource exploitation in the same product system is ensured by the product and materials reuse/recycling.	LA + LB + LC LA = initial lifetime contribution LB = refurbished lifetime contribution, time periods that a product is used in an ith cycle x proportion of the initial resources that are eventually reused. LC = lifetime created by the process of returning products, dismantling and recycling them	9, 35, 49
160	Material Use Efficiency MUE [%]	It represents an appropriate value for quantifying the recovery of by-product.	∑ material consumed + ∑ material disposed) / ∑ material consumed	9, 29, 35, 49
161	Circular Economic Value [%]	It aims to illustrate the effects of the renewable materials and energy resource usage. $100 - \left(\frac{\left(\overset{\overset{M_{lin}}{\Downarrow}}{\frac{M_p}{M_p + M_s}} + \overset{\overset{M_{lout}}{\Downarrow}}{\frac{M_d}{M_r + M_d}}\right) + \left(\overset{\overset{E_{lin}}{\Downarrow}}{\frac{E_f}{E_s + E_f}} + \overset{\overset{E_{lout}}{\Downarrow}}{\frac{E_l}{E_c + E_l}}\right)}{4}\right) \times 100$	Mlin/Mlout = Material volume on the input/ output side; Mp/Ms = primary/secondary raw materials used for the process of the product Md/Mr = non-recyclable/recyclable materials remaining after the product is used; Elin/Elout = Energy value on the input/output side Ef/Es = Non-renewable/renewable energy used during the manufacturing of the product El = Energy produced during disposal, after the product was used; Ec = Energy used for the product's recyclability, after the product was used	9

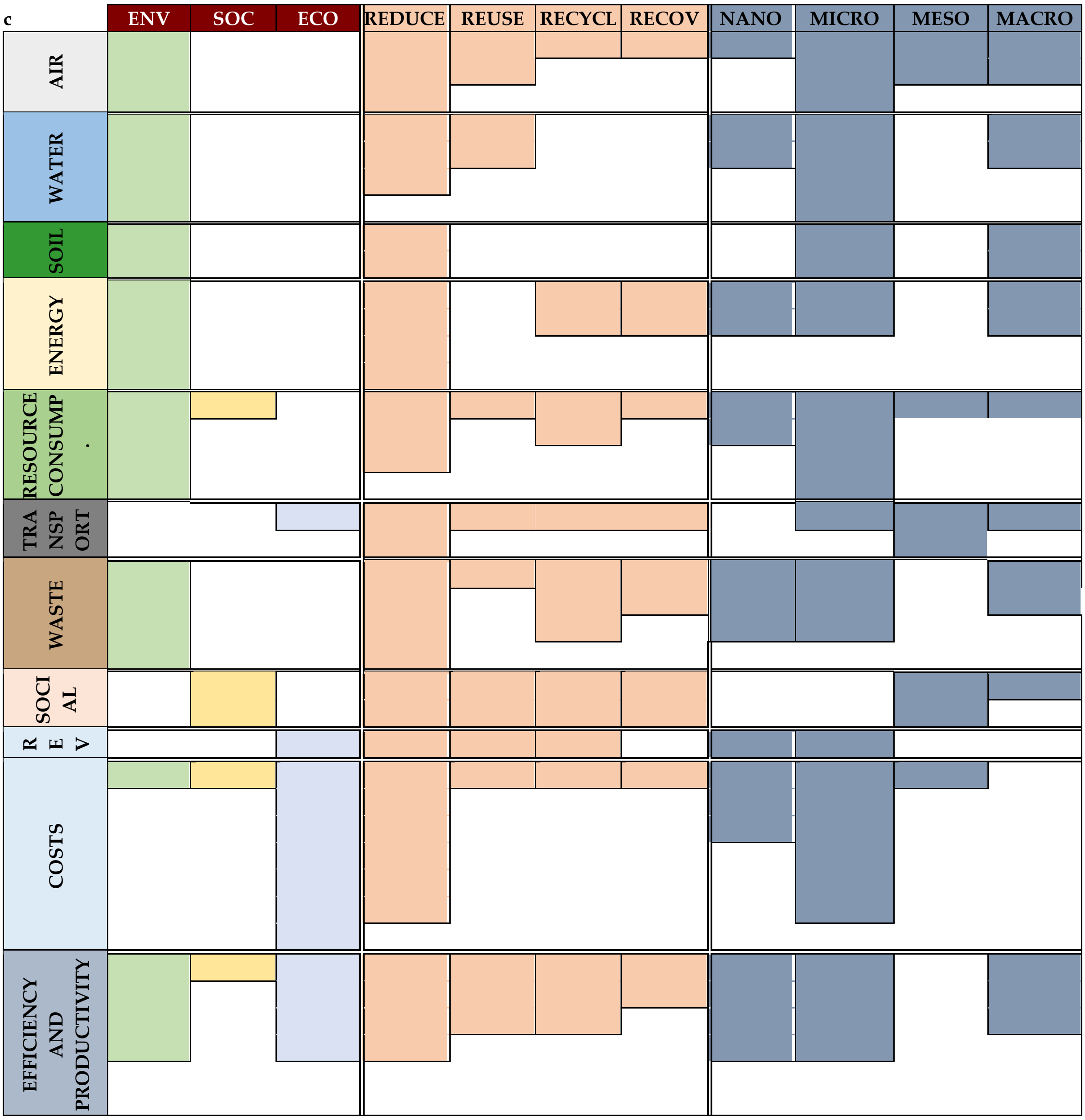
	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
162	Circularity Index [%]	It takes account of losses in both quantity and quality when reprocessing materials.	$\alpha \cdot \beta$ α = recovered EOL material / total material demand β = 1 – (energy required to recover material / energy required for primary production)	9, 39
163	Modified Material Circularity Indicator MCI [number]	The modification of the MCI creates an index devoted to biological cycles. In a zootechnical system, the mass V of virgin raw material is related to the animals and their feed.	1 - LFI(V) * F(X) LFI(V) = Linear Flow Index of a product, V = Mf/FCR + Ma, FCR =feed conversion rate in a production; Ma = initial mass of the animal, Mf =feed mass; F(X) =quantity of linear flow by the expected utility of the product relative to the industry average (X)	9, 25
		PACKAGING INDICATORS		
1	Energy consumption for disassembly [kWh]	Energy consumption to disassemble partially or completely the product, in order to reuse, remanufacture, refurbished its components or recycle it	Energy consumption of destroying the connection of the part i x the number of parts	19, 59
2	Packaging per Packaging Level [mass]	Amount of packaging mass utilised in each level of supply chain which required it (subretail, retail, merchandising, traded and pallet)	Mass of packaging use per packaging level (subretail, retail, merchandising, traded and pallet)	14, 59
3	Packaging Material Summary [number]	Amount of each individual packaging material in the overall system format, allowing to get an overview of all the packaging material used to package products	Number of each individual packaging material in packaging system format	14, 59
4	Packaging mass fraction [dimensionless]	Amount of packaging mass compared to the total mass of the products. Attempt to reduce this indicator's value to reduce quantity of waste.	Packaging mass (kg) / total mass of products (kg)	14, 59
5	Packaging materials from suppliers [kg]	Amount of total packaging materials received from suppliers, considering the raw materials packaged used for manufacturing a product	Total packaging mass received from suppliers	14, 59
6	Efficiency of packaging design [number]	This indicator measures the efficiency of packaging design, through the number of units packaged together	Number of units packaged together for storage or transportation	14, 59
7	Re-packaging [number]	Amount of times product is repacked throughout supply chain	Number of times product is repacked throughout supply chain	14, 59
8	Number of Different Materials [number]	Amount of different materials identified in packaging	Number of different materials in the packaging product	14, 59
9	Number of Components [number]	Amount of different components in packaging	Number of components of the packaging product	14, 59
10	Number of Reversible Joints [dimensionless]	Amount of reversible joints to the total number of joints of a product	Number of reversible joints/Number of total joints	14, 59
11	Component Type [dimensionless]	The connection type between components in a product reflects how difficult is to destroy the connection	$\sum C_i/n$ C_i = interactive factor of connection for part i n = number of connections.	14, 59
12	Total number of fasteners [number]	Amount of fasteners in the product	Total number of fasteners in the product	14, 59
13	Intelligent Materials [dimensionless]	"Intelligent materials" are materials which undergo reversible physical or chemical changes under variations of magnetic or electrical fields, they can repeat this process without losing their original properties	Weight of clever materials/Total weight of the product	14, 59
14	Polystyrene Foam Usage [%]	Amount of polystyrene foam usage. Polystyrene Foam is valued for its insulating and cushioning properties even if its recycling is not feasible at the moment	(Weight/volume of Polystyrene Foam used in the product & packaging by total Weight/volume of product) x 100%	14, 59

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
15	Product Biodegradable Packaging [%/product]	Amount of biodegradable packaging to the total packaging per product manufactured. Attempt to increase this indicator's value to facilitate proper treatment of the end of life.	Percentage of biodegradable packaging per product	14
16	Packaging Recyclability [dimensionless]	Amount of recyclable materials in packaging	Recyclable packaging material mass/Total packaging mass	14,, 63
17	Packaging Reusability [dimensionless]	Amount of total reusable packaging mass used to total packaging mass	Reusable packaging material mass/Total packaging mass	14
18	Take back packaging from post use [kg or m^3]	Indication of post use packaging mass/volume received from consumers/buyers of a product in order to reprocess it	Mass (or volume) of used packaging returned to production plant for reprocessing	14, 59
19	Take back packaging from pre-use [kg or m^3]	Indication of the pre-use packaging mass/volume received from internal facilities which can be packed and transported internally between factories and facilities	Mass (or volume) of used packaging returned from internal facilities and factories	14, 59
20	Discarded Packaging Materials per Product [kg/product]	Amount of packaging material discarded per product. This indicator can be measured for the users, i.e. the packaging they discard	Mass of packaging material discarded per product	14, 62
21	Packaging Scrap [kg/product]	Amount of packaging scrap per product manufactured	Mass of packaging scrap per product manufactured	14
22	Packaging to Landfill [% or kg]	Amount of packaging used to landfill (i.e. packaging that is not reused or recycled). It can also be measured to the total packaging used, as a percentage	Total mass of packaging use destined to landfill	14
23	Recycled plastics usage [%]	Amount of recycled plastics usage as percentage of total plastic in packaging in terms of mass or volume	(Recycled plastics usage /Plastics usage) x 100	14, 59
24	Recycled paper usage [%]	Amount of recycled paper usage as percentage of total paper weight in the packaging product.	(Recycled paper usage/Paper usage) x 100	14, 59
25	Recycled Containerboard usage [%]	Amount of containerboard used in the packaging	(Weight of recycled containerboard/Weight of containerboard) x 100	14, 59
26	Take-back offering for products [%]	Number of customers that are offered contracts for packaging with a take back option at the end of product's life or use cycle	Number of contracts (or customers) for products offered with a take back option / Total number of products sold) x 100%	14, 64
27	Packaging costs [EUR/UP]	Cost of materials associated with packaging of a product	Total amount of material type j purchased for packaging (m^3 or kg) x price for m^3 or kg of packaging type j / total number of product units made (UP)	14
28	Take back cost [EUR]	Costs incurred by a company for take back option of packaging which requires reverse logistic in place as well as requires involvement of product users	Number of products ordered to be taken back (Yi) and the cost of collecting each product of type i.	14
29	Total sorting cost [EUR]	Total sorting cost, i.e., cost to sort materials/parts for further re-use, recycle and recovery. Sorting is needed to separate valuable parts and materials for proper re-use, recycling or recovery.	Cost to sort a discarded product of type j (or material type m) x a quantity of accepted returns of product type j (or material of type m)	14
30	Cost of transportation in reverse supply chain [EUR or EUR/unit]	Cost of transportation in reverse supply chain which depends on the total distances travelled in reverse supply chain (collection of packaging at the customer, delivery to the disassembly/remanufacturing site to either another supplier or original manufacturer)	([Transported distance / fuel consumption] x cost of fuel / Total qty. of used products/parts/materials transported) x information sharing cost and ordering cost	14, 64

	Name of the indicator	Detailed description and purpose of indicator	How to measure the indicator	Ref.
31	Disassembly Effort Index DEI [%]	Total operating cost supported dismantling a commodity. The finding is to achieve an economic estimate, a valid evaluation that can be utilized in disassembly decision making	Seven are commercial infrastructures considered: time, tools, texture, access, instructions, risk, and force requirements. The aim is to estimate each factor for each stage on a cost/effort indexing rank, specified in the 0 to 100 scale. The sum of the DEI scores for all steps gives the overall score.	19, 41, 49, 60
32	Cost of non-destructive disassembly (CND) [EUR or EUR/UP or EUR/product]	Non-destructive disassembly is the systematic process of removing parts from an assembly whilst ensuring that no damage occurs as a result of the process	number of items to be reused (Xij) and stored (Vij) x cost per hour (cnd) x the time of disassembling each item (dtj)	19, 64
33	Cost of destructive disassembly (CDD) [EUR or EUR/UP or EUR/product]	Destructive disassembly involves separating materials for recycling. Destructive disassembly is focusing on materials rather than items	number of items to be recycled (R) and disposed (D) x the cost per hour (cd) x the time of disassembling each item (ddtj)	19, 64
34	Material Circularity Indicator MCI [number]	It allows firms to recognize added and circular value of their products, materials and components, and attenuate hazards derived from price volatility and supply	1 - LFI * F(X) with LFI = amount of material which flows in a linear way, F(X) =quantity of linear flow by the expected utility of the product relative to the industry average (X) and X = ratio of expected lifetime (L) to the expected industry average life	35, 47
35	Product - level Circularity Metrics PLCM [dimensionless]	Economic value of recirculated packaging parts (recycled and refurbished) and the economic value of all parts to calculate product circularity, which is defined as the fraction of a product that comes from used products	Economic value of recirculated elements/economic value of all elements.	35, 49
36	Number of disassembly tasks [number]	Amount of disassembly tasks. Attempt to reduce this indicator's value by designing products with fewer components/parts.	Total number of disassembly tasks	19, 59
37	Operation Time/Disassembly Time [time units]	It is used to calculate the indicator "Disassembly Time of Each component"	Time for aligning between tool and joint element (Tdal) + Time for tool operation area (Tda) + Time for basic separation of joint element (Tdb) + Time for intensity of work (Tw)	19, 59
38	Disassembly Time of each component [time units]	This indicator is measured by the sum of the indicators "Preparation time", "Movement time", "Operation time" and "post-processing time"	Preparation time (Tp) + Movement time (Tm) + Operation time (Td) + post-processing time (Tpr)	19, 49
39	Disassembly time of the product [time units]	This measure of the disassembly time of the packaging product is the sum of the disassembly time of each component,	Sum of the disassembly time of each component of the product	19, 49
40	Number of Tools for Disassembling [dimensionless]	Amount of tools required for disassembly the product	Number of necessary tools/Number of total joints	19, 59
41	Hand manipulations [number]	This indicator quantifies the number of hand manipulations required in disassembly	Number of hand manipulations	14, 59
42	Number of parts to be disassembled [number]	Number of parts of the packaging to be disassembled	Actual number of parts to be disassembled	14, 59

Table 7 shows the result of the categorisation and clustering process applied to the mentioned indicators. It presents the proportional allocation of indicators divided by the selected dimensions. Presentation of complete table, with the individual KPIs allocated to the various categories, can be found in Appendix B. Through the targeted use of these indicators in relation to the contexts in which the CE is deployed, the framework offers a toolset for guiding decision-making processes and tactics.

Table 7 – Distribution of indicators by clusters and categories



4.2 Results of classification analysis

The discussion presented in this Section regards the analysis of the metrics divided by categories.

The discussion is limited to food indicators, excluding those specific to packaging that have been found, since their relevance in both numbers and significance is lower.

The section is structured in three paragraphs according to the three categories applied, but the analysis conducted inside each paragraph is integrated between them, to give more value to the findings obtained and to obtain an integrated view.

4.2.1 Triple Bottom Line

The diagramm shown in Figure 7 presents the distribution of indicators per Triple Bottom Line pillars. The distribution of indicators reflects what emerged from the literature: environmental and economic indicators are respectively 72% and 29 % of the total indicators, while the social ones are 10%. The low percentage of this last perspective is due to the choice of perspective adopted for this dimension. Since it was decided to focus this aspect mainly on the development and monitoring of the awareness adopted by the various actors, the number of indicators, which was already low, was further reduced. Therefore, it is essential to include these few metrics in the circularity assessment in order to include a broader vision.

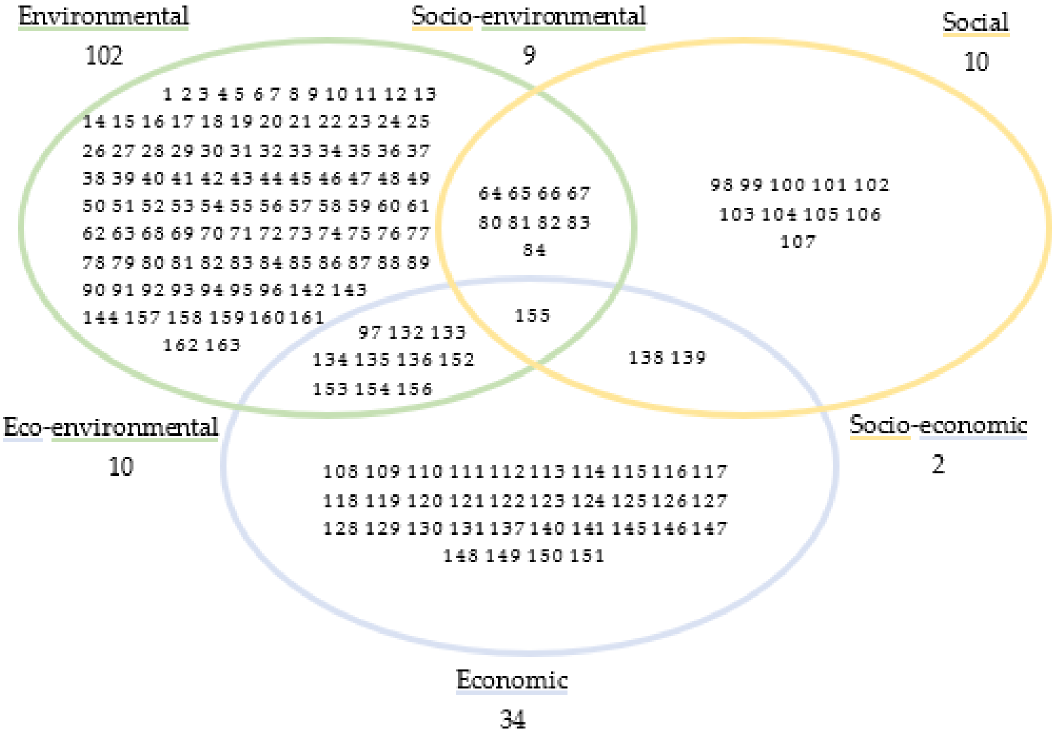


Figure 7 - Distribution of indicators per TBL pillars

Since the table wants to collect indicators that can be easily implemented, indicators impacting on several pillars are few (10%), because they require data from different sources and are difficult to acquire, integrate and compare. Most of those consider environmental and economic dimensions, in line with the fact that these aspects are the core ones of the Circular Economy. In order to calculate these typologies of integrated indicators, data from different areas are required. Since this is not always feasible, but at the same time it is important to obtain a more complete and holistic view, it will be necessary to develop a method to consider and compare the three perspectives.

A last consideration regards the fact that some indicators in the table measure has the same objective of analysis but from two different perspectives: one in environmental terms and the other in economic terms. Although it seems redundant to include both types of indicators, it is important to maintain them to allow for a comprehensive evaluation.

4.2.2 CE strategies

Analysing the distribution of indicators according to CE strategies, the majority (85%) rate the performance of the reduction strategy, in line with the Food Waste Hierarchy that suggests prioritising this policy over the others. Nevertheless, achieving this goal will be challenging given the projected growth in consumption because population is increasing. If on one hand goods demand will grow, on the other hand there are fewer and fewer natural resources available. Thus, it will also be necessary to focus heavily on the social aspect by involving customers in adopting a more conscious consumption. Companies can reduce the resources they use to a certain extent: responsible production must also be coupled with responsible consumption, in accordance with SDG 12. Indeed, three out of four social indicators also include reduction strategy, which can be understood more as Prevention in accordance with the Food Waste Hierarchy. In this perspective, indicators that measure the collaboration between the company, customers and other actors in the supply chain, such as *Number of campaigns on responsible consumption* (98), *Availability of customer support option* (99), *Contribution to local initiatives* (100), are essential to include.

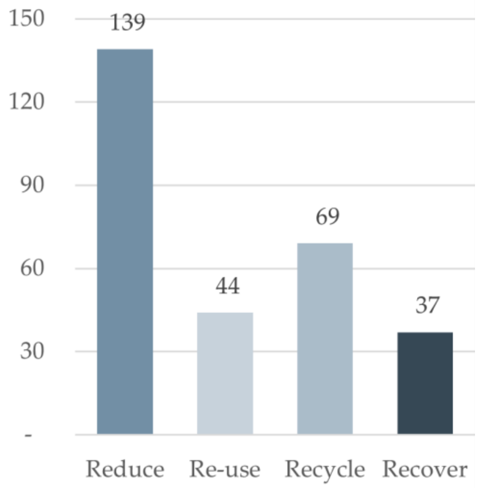


Figure 8 – Distribution of indicators per CE strategies

27% of indicators aim at reuse policies, declined in the activities of 'Redistribution for human consumption' and 'Reuse for animal feed' to reduce waste production. The social level is particularly relevant for this policy that can be adopted especially in the perspective that the benefits obtained do not only favour the environment or costs, but other people and their lives. However, what the data show is a not particularly high number of social indicators with an impact on reduction (20%).

According to the Food Waste Hierarchy, if the food isn't edible anymore and it has become a waste, it's not possible to implement Reduce or Re-use strategies, but Recycle and Recover ones. It is positive that half of the indicators are aimed at recycling strategies, which, according to the pyramid, is the preferred one to implement when dealing with waste management. It is interesting to note that the implementation of these strategies involves an additional use of resources to implement the process. For this situation, it is therefore important to study the total result of implementation beforehand to see if there are any sustainable benefits. Indeed, some metrics aim at assessing more the achievable benefits rather than the negative impact caused on the environment and the economy. Lastly, it is noteworthy that 23% of the indicators aim at assessing the impact on recovery, despite the fact that this should be the last option before disposal.

The three sustainability pillars are distributed differently in each plan, as it can be seen by looking at this distribution graph in Figure 9Figure 9.

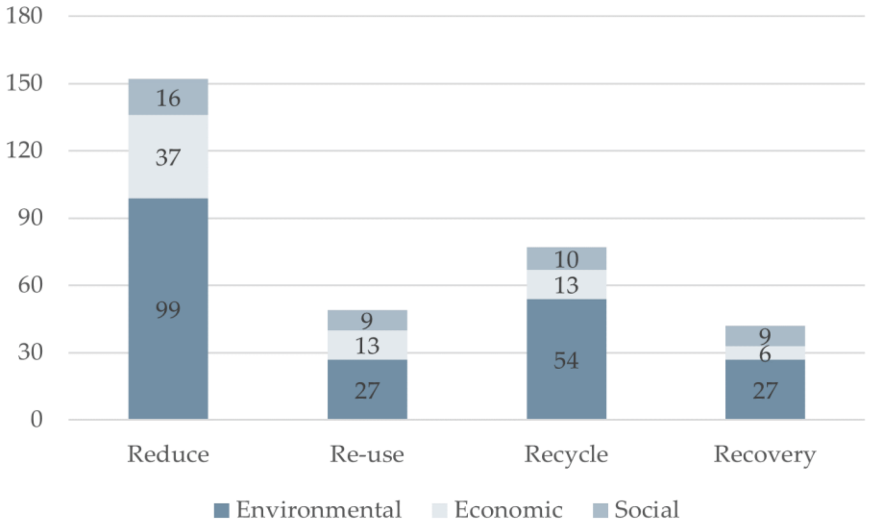


Figure 9 – Distribution of indicators divided by CE strategies per TBL

Environmental metrics dominate in all categories as expected. Only 'Recover' strategy shows a different trend than expected, containing more social indicators than economic ones. This can be explained by the fact that the decision to adopt a process in which waste is transformed into energy resources requires consumer awareness in favouring this type and therefore a good number of metrics are needed to monitor this trend and incentivise it.

Moreover, it is remarkable that social indicators are present almost in double figures in the reduction strategy, underlining how important it is to adopt the prevention approach.

4.2.3 Levels of analysis

The goal of the table is mainly presenting indicators useful for decision makers to evaluate circular activities and their impact inside the company. So, it is reasonable that 69% of indicators can be applied at micro level and 34% at nano (Figure 10). This last level of analysis is often not considered by authors in the literature but can provide useful insights to understand what to work on and improve at the individual product level. Some micro and meso indicators can also be useful to measure at the macro level (30%), since they affect elements that can go beyond company boundaries and are worth analysing at a more aggregated system level, such as *Total land area used for production* (35), *total area equipped for irrigation* (36), *Index of livestock, food and crop production* (142, 143, 144), *Intensity of transportation* (95). On the other hand, only 15% of indicators affect meso level, although collaboration between different actors in the supply chain is crucial for the implementation of EC in the food sector and in waste reduction.

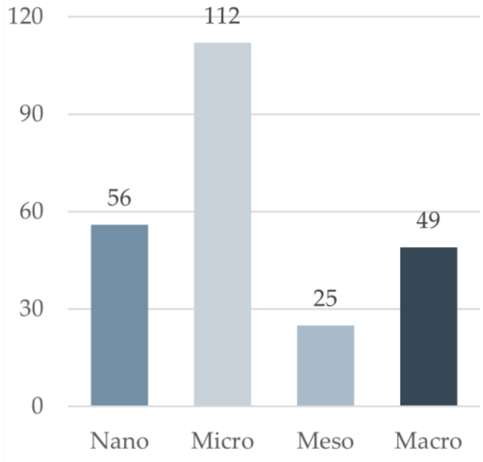


Figure 10 – Distribution of indicators per levels of analysis

Cross-analysing the strategies and the level of detail applied (Figure 11Figure 11), two trends can be highlighted. Economic and environmentally based metrics are most applied at nano and micro level, based also on the fact that the data required to assess them are less complex to collect compared to social ones. On the other hand, the results show the importance of supply chain involvement in CE implementation, express by the fact that the highest number of social indicators regards meso level, and thus contribution from other actors of the supply chain.

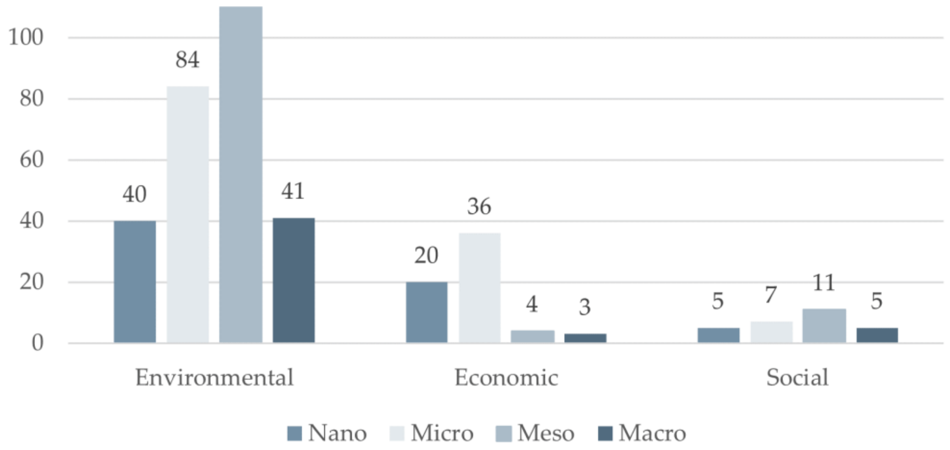


Figure 11 – Distribution of indicators divided by TBL per levels of analysis

4.3 Results of cluster analysis

This paragraph aims at highlight considerations regarding the combination of clusters created in relation to the categories (TBL, CE strategies and level of analysis).

The configuration of the overall dashboard has already been presented in Table 7. Figure 12 – Distribution of indicators per clusters shows instead the proportion of KPI included in each cluster.

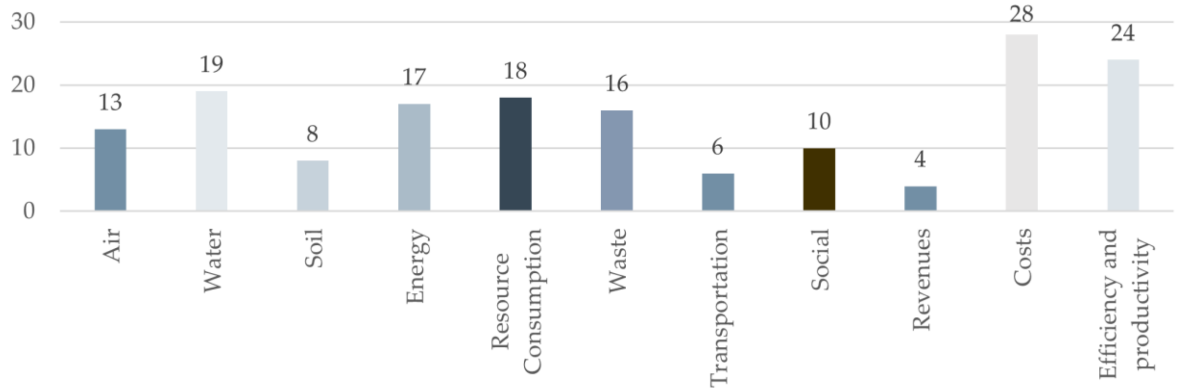


Figure 12 – Distribution of indicators per clusters

The first four clusters (Air, Water, Soil, Energy) include only environmental indicators, which focus on quantitative and qualitative aspects related to the management of the specific natural resource that needs to be preserved. The corresponding indicators of an economic nature are present in the "costs" and "revenues" clusters, obtaining a balance to create a complete view. All of them are extremely focused on applying reduction practices, in order to decrease the quantity of materials used and not pollute or waste them, since they are critical and limited. Food companies are equally interested in these four branches because they are all impacted every time in the production process of an agri-food product. Moreover, these indicators are important to assess at macro perspective since the resources are public good (even if some can become private) and therefore should be constantly monitored and so that they are not contaminated and harmful to people's health.

For what concern 'Waste' and 'Material and resource consumption' clusters, the indicators included are divided by reduce and recycle strategies, which are respectively the priority approaches to adopt based on Food Waste Hierarchy. Micro indicators are the most present, followed by nano, since it is interesting to analyse the percentage of resource and waste produced by the single material and product. These clusters lack of meso indicators, which can be interested to include involving other actors in the development of circular practises. They play a critical role because the materials require attentions and specific conditions to satisfy, which are often due to third parties.

Transport-related indicators analyse environmental parameters and must be taken into account in logistics optimisation processes. They provide not only measures to be applied within the company, but also metrics involving other actors and achieve and integrated view. Transport phase is critical when dealing with food because it requires special prerequisites and standards to be maintained, which sometimes involved even more material consumption than the movement of a manufactured product. Therefore, parameters need to be checked to optimise the output and the business.

'Social', 'Revenues' and 'Costs' gather indicators which are the social and economic counterparts of the metrics presented in the previous clusters, allowing them to focus primarily on these aspects.

Lastly, 'Efficiency and productivity' indicators apply a broader and holistic view, considering both economic and environmental aspects. Moreover, it can be applied to all strategies. The breadth of measurement does not matter as far as the level is concerned, since most KOI are useful tools for improving competitive performance and therefore apply to a level of analysis that does not go beyond the boundaries of the company.

5 A proposed framework to select indicators

The table of indicators with the related classifications and clustering described in chapter 4 aims to collect all the most frequent circularity indicators found in literature and applicable to the agri-food sector. In response to the research question, a framework is now presented to help decision-makers select from this table the most suitable circularity indicators for their business and needs.

The pool of metrics is helpful for understanding in detail which specific aspects need to be improved in order to obtain greater benefits from the implementation of Circular Economy. Therefore, it can be used by decision-makers when they need to understand which strategies or corrective actions to adopt. Since the number of indicators in the table is high and users can select the metrics they consider most suitable, the chances that many companies adopt the same indicators decrease and therefore benchmarking becomes more complicated. Indeed, this methodology has been developed taking into consideration the need that emerged from the literature review to customize the circularity assessment and the indicators included in it based on specific contexts, conditions and needs, especially in the agri-food sector where the implementation strategies of Circular Economy are more particular than those of the other sectors, which instead are positioned more towards the technical side of the butterfly model. Therefore, it is important to underline once again how this methodology is useful for analysing the situation in detail, while instead if the measurement is carried out for benchmarking purposes it could be more useful to use composite indicators which adopt a more holistic perspective, standardize the elements to be measured for the calculation and facilitate the comparison between companies.

After this premise, it is also important to illustrate the different cases in which this methodology can be applied. In particular, decision-makers may be faced with the choice of replacing the current Linear Economy with a more circular model and therefore want to perform a cost/benefit evaluation of this transition. Alternatively, they may have already decided to implement a circular system and would like to carry out an ex-ante assessment in order to understand which CE strategy would bring more benefits. Finally, if a company was already adopting a circular model, the methodology could be applied to evaluate its level of circularity and identify any strengths or weaknesses to improve.

In all these cases, the proposed framework recommends starting by identifying the level of analysis to be adopted, thus choosing between nano, micro, meso and macro following the classification suggested by De Olivera et al. (2021). By applying this filter, an initial skimming of indicators is performed and the perspective to be adopted in measuring the impact of decisions is clearly defined, thus choosing between the focus on the impact of a single product, of the company or that generated on even larger scales. The analysis of the current situation shows that the majority of companies have applied indicators from the micro level (Baratsas S. 2022, Kristensen H.S. 2020, M. G. Roos Lindgreen E. 2021), but it has been shown how important is to involve broader levels in the analysis. As presented in a case example from Dani (2015), a dairy farm belongs to a complex value chain, since the product can be input for several other processes. Adopting a meso perspective in circularity assessment would include also the impact of these other actors in the evaluation. Instead, agriculture-related activities have impacts beyond the company's boundaries, as they produce emissions related to land, water or air, which are common goods within a nation or region, and thus may in turn influence the performance of other companies operating in the same area. Consequently, adopting a macro view in the management of these aspects can produce a greater benefit.

After this first step, it is possible to apply another filter on the three pillars of the Triple Bottom Line. In general, it is always advisable to consider indicators belonging to all three sustainability dimensions in order to maintain a more holistic approach and try to improve in all the relevant aspects of sustainable development. As underlined in the previous chapter, although social indicators are much less than the environmental and economic ones, the social impact generated by the Circular Economy in the agri-food sector can be extremely large. In this context, it could happen that, for example, a company already applies other sustainability assessment methods focused on environmental and economic aspects. As has emerged from the literature the concept of sustainability is often reduced to environmental (and sometimes economic) considerations (Ahi P. 2015, Joung C.B. 2013). In that case, the decision-maker may decide to consider only the social indicators present in the table in order to integrate them into the other already existing framework. This example can also apply to economic and environmental dimensions. However, given that the purpose of this table is to collect the most suitable indicators for measuring circularity in the agri-food sector, it is still advisable to consider all three pillars at the same time in order to address the new challenges this sector has to face replacing the old metrics with new ones. Looking again at the agricultural farm case, in this step, it can decide to include the three sustainability dimensions by selecting macro indicators which cover all aspects. Starting from an environmental perspective, the company can monitor a particular aspect of energy, water, soil, air, waste, and resources management based on its core business. Then, it should select a social metric to promote the commitment towards the achievement of environmental indicators involving local communities. Lastly, it should monitor the effectiveness of these aspects by adopting an economic perspective.

The CE strategies filter choice follows a similar approach as the one mentioned for the TBL filter. Considering the various use cases of this methodology described at the beginning of this chapter, the framework proposes several solutions. If the purpose of the evaluation is simply to calculate the costs and benefits of an already circular system, it is possible to filter only the indicators related to the applied strategy in order to better identify any areas for improvement. If, on the other hand, the aim is to compare different CE strategies with each other in order to assess which would bring the most benefits, it is possible to either avoid applying the filter or filter only those strategies with the highest potential. Of course, it is always advisable to respect the priority scale suggested by the Food Waste Hierarchy, favouring strategies for food waste prevention rather than management. Finally, the same reasoning applies also when the objective is to compare a Linear Economy model with a circular one. Consider, for example, an agriculture company that has recently decided to implement a reduction strategy to decrease the impact generated by its extensive water use. In this case, it might decide to focus only on the indicators of the reduce strategy and monitor the environmental, social, and economic benefits achieved over time. If the implemented strategy proves successful over time, it could decide to go further in the future and evaluate whether to redistribute or recycle the remaining waste that it still continues to produce and then evaluate the benefits of implementing additional CE strategies or not. Considering only the reduction strategy, indicators would be very focused on consumption, waste, and cost, while reuse indicators might emphasize more on ethical and social benefits.

At this point, the company that has decided to implement this proposed framework can decide whether to consider all the remaining indicators or select only the more relevant ones to focus on. However, in the latter case, it is important not to cherry-pick the indicators, even if unconsciously. Indeed, as pointed out by several authors in the literature, the risk of tailoring the set of indicators is to select only those that are most advantageous and that return beneficial values to report that nevertheless do not help identify possible areas for improvement. It is, therefore, necessary to identify the right trade-off between the advantage of having a customized and context-specific set of indicators and the risk of having biased decision-making and running into possible greenwashing incidents. However, considering for example environmental indicators, it is evident how an agricultural company cannot neglect indicators on water, soil and energy use, while instead fish breeding and livestock farming companies must necessarily monitor waste generation. Finally, diary companies should not neglect the transportation aspect, as production chains often involve several actors before reaching the final customer.

In parallel with this selection, it is also important to understand whether the considered indicators are measurable or not. Indeed, companies often struggle to collect all the data needed to measure indicators. This is even more difficult when metrics require the measurement of data that also involves stakeholders outside the company, such as other supply chain actors. However, several studies have stated the importance of involving external stakeholders in the assessment, especially in the context of the Circular Economy, where collaboration with external partners is critical for the achievement of meaningful results.

Although indicators in the table have precise definitions and formulas derived from the literature, the framework does not exclude the possibility for users to customize the indicators in order to make them more suitable for their specific context. However, using the standard metrics ensures more reliability and is more suitable for benchmarking with companies that have measured the same indicators.

When the final set of indicators has been identified and all data have been measured, the results obtained are useful in identifying areas for improvement or suggesting areas with the most potential for Circular Economy implementation. Of course, in order to understand whether achievement is good or not, it is necessary to set targets. It is possible to do this by following national and international standards, which are increasingly emerging due to the growing attention on sustainability and particularly in the agri-food sector. Alternatively, it is possible to set targets based on the performance of similar companies operating in the same sector, making benchmarking the key to push companies toward a more sustainable future.

Moreover, it is also recommended for companies to monitor their performances over the years in order to understand whether the choices made proved successful or not. In this sense, the proposed framework, therefore, suggests a method for building a set of indicators to measure circularity in the agri-food sector to support decision-making in future choices, monitoring the results of these choices over time and comparing them with those of similar companies.

The following flowchart (Figure 13Figure 13) describes the framework just presented for selecting the right set of indicators to measure the circularity performance of companies in the agri-food sector.

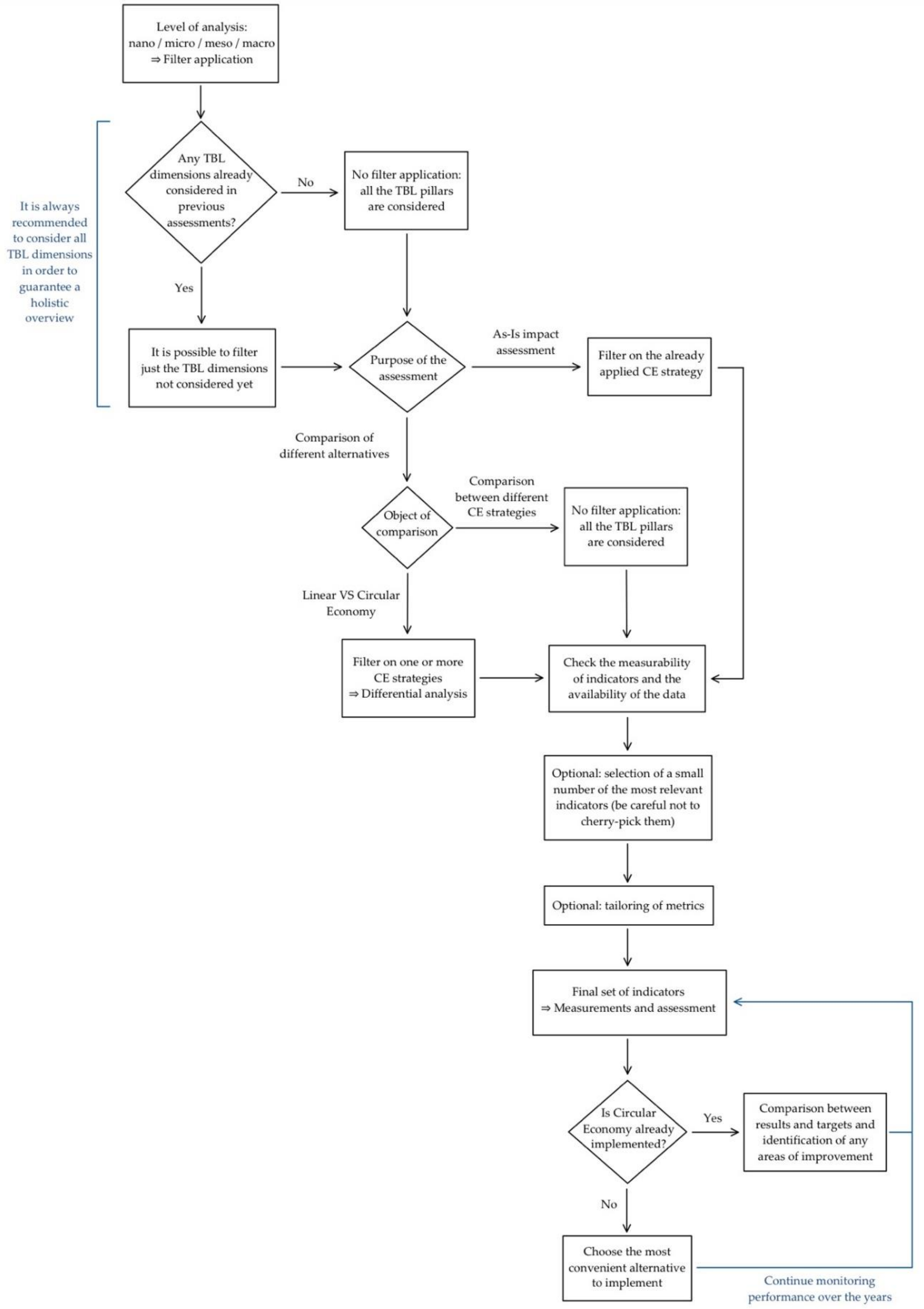


Figure 13 – Flowchart representation

6 Conclusions

Problems related to the management of the population's sustenance for the coming years have evolved rapidly in recent years and are expected to continue to grow exponentially in the future. Indeed, one of the key issues of the next years will be meeting the world's food demand (van Dijk M. 2021) due to the increase in world population and at the same time the scarcity of earth's resources (Silvestri L. 2022).

Food companies are directly impacted by these trends, and they have to act consequently in order to manage appropriately the requests, and therefore productions, in terms of inputs and output flows.

Sustainability has been identified as a proper solution, but it will not be enough for dealing with the required quantity of natural resources, such as soil or water, needed to produce agri-food goods. In particular, food businesses should introduce Circular Economy practises, which have been identified as a solid solution to the pursuit of Sustainable Development (Muscio A. 2020). As reported by the literature review articles, corporate decision-makers are provided with a wealth of possible approaches that they can introduce and apply to the business and evaluating methodologies which measure the effectiveness of approaches implemented (Elia V. 2017).

Among these several frameworks used to implement and assess circularity, three approaches were identified as relevant: EWF Nexus, Food Waste Hierarchy and KPIs. These tools contribute to managing properly resources by reducing external inputs, waste and emissions, closing production loops and so reutilising and repurposing materials, while indicators have been indicated as an" important tool for aiding progress towards a successful transition to Circular Economy" (Cayzer S. 2017). The benefits that indicators have over other various frameworks and models concern their abilities to represent a precise goal to be achieved, measure and monitor it, and track its progress or backwardness by being able to make comparisons. This implies that they are highly valued by companies because they reflect simplified management of performance measurement. Literature also recognizes these benefits brought by the indicators to the point of presenting a large number of metrics that can be used to make decisions.

From these considerations, it was possible to identify the gap. The presence of such a high number of indicators is not accompanied by a unified and unambiguous method for their selection based on the specific characteristics and needs that each company has.

The proposed research aims to fill the gap by providing a table of indicators composed of filters and categories, which help the selection of the most suitable metrics. The first purpose of the table is to group the various indicators scattered throughout the articles and reports analysed, creating uniformity and a solid base from which companies can apply a transition to more circular models.

The resulting dashboard is composed of heterogeneous sets of parameters and filtered on the core aspects of circularity in the food sectors. The selected methods – EWF Nexus, Food Waste Hierarchy –allowed decision-makers to select these key elements which are necessary to consider when dealing with circularity inside a food company and therefore acting as drivers in the decision-making process.

Since CE indicators presented in the table are primarily aimed at businesses and companies' decision makers, there is a preference for the practical use effectiveness, focusing on single-valued measurements, which have a limited amount of information to collect, and which can be better applied to different companies. In this way, communication and simplicity benefits are achieved (Cayzer S. 2017, Kristensen H.S. 2020). On the other hand, aggregate metrics would create more complex challenges for the companies that operationally have to implement these solutions.

The output obtained through the application and evaluation of these indicators show the development of a company towards Sustainable Development.

6.1 Theoretical implications and contributions to literature

This study contributes to the existing literature by meeting the research questions presented before.

Literature has highlighted how the evaluation of CE techniques becomes fundamentally relevant if a circular system has to be reached. However, companies currently assessing circularity strategies face some challenges due to theoretical confusion.

First, this study presents a clear position of the goal of Circular Economy indicators. The selected metrics can be meaningful to assess the value of a material, product or process, to which it was applied a circular strategy. 10R framework is a suitable tool to identify these typologies of indicators and distinguish them from the ones that aim at assessing the sustainability of Circular Economy approaches. It can be stated that Circular indicators included in this thesis "act as a means to achieve a goal, which is reflected in the impacts. This is very much in line with what the CE holds as core principles" (Garcia-Saravia Ortiz-de-Montellano C. 2022).

Furthermore, the created dashboard collects the main circularity indicators which can be useful for the food business. The obtained results make significant contributions to the decision-making process of companies belonging to this sector: the core aspects of the table, compared to existing frameworks and methods, are the inclusion of metrics easy to implement in a unique set and at the same time the ability to capture the complex value of the system, as an integrated supply chain subject to dynamic events, by simultaneously taking into account more value domains (Iacovidou E. 2017).

The latter aspect has been presented as critical by several authors, who presented it as an element of future research and to be addressed in order to obtain a holistic vision as well. The proposal faces it by providing several categories and clusters and therefore considers more dimensions of analysis when performing a circularity assessment. The different classes bring more clarity since they allow quick identification of the possible areas on which to act. On the other hand, this process leads to the division of indicators. The result runs the threat of isolating the concepts rather than integrating them to achieve a comprehensive interpretation of circularity and a holistic approach. To tackle this issue, the suggested guiding procedure, based on several steps, is introduced allowing companies decision-makers to start from the simple metrics and gradually add more and more elements to the analysis carried out. Applying this process permits the inclusion of more factors inside the evaluation and, at the same time, avoids the use of composite indicators. This category has been promoted by some authors in order to gather more information into a single value and achieve an integrated perspective, but its applicability is often limited due to the efforts required for data collection and comparison.

6.2 Managerial implications

The study is addressed mainly to decision-makers, who play a critical role in managing change towards more circular business models. Their goal is to address the innumerable sustainable issues that have emerged and will continue to grow through not only the choice to adopt circular practices but above all their control and evaluation to assess whether the path that has been decided is actually to travel is the correct one. Their task is made difficult by the complexity of the sector in terms of the product offered, production needs, and actors involved. Moreover, their range of action can also be limited since it cannot influence the control of shortages of natural resources or climatic consequences that the food sector suffers.

Innumerable indicators have been proposed with the main purpose of describing and involving as many cases as possible. but thus, also creating more complexity and confusion.

The proposed set of indicators can primarily serve to limit the choice and restrict it to a narrow field, thus allowing different companies to draw from the same set and creating more uniformity also in the same supply chain.

Furthermore, the framework allows to navigate easily between the metrics and choose the ones that best suit their needs, avoiding the use of composite indicators.

Decision-makers are called to make choices concerning not only strategies for changing from a linear model to a more circular one, but also to define which circular aspect is better to pursue. The guidelines help to identify the priority elements inside the company which require attention, for example, they have a significant impact on environmental, economic or social systems. Once identified the factor to improve, it is possible to analyse it under different aspects and with different criteria. First, the framework enables the selection of the area which reflects the specific internal requirements of the company, such as the goal of achieving effectiveness or improving water, energy, and resource management. So, managers obtain a limited number of possible indicators more suitable for that specific request. Once the area of selection is narrowed, criteria based on circularity requirements can be considered in terms of the level of analysis (nano, micro, meso, macro), CE strategies involved (reduce, reuse, recycle, recover) and TBL aspects (environmental, social, economic).

6.3 Limitations and future research implications

This paragraph underlines the main limitations of the study and suggests directions for future works.

The decision to create a unique and uniform dashboard of indicators to standardize the system has some drawbacks. Some businesses prefer to create their custom assessment methods to better reflect the reality of the company (O. K. Roos Lindgreen E. 2022). This process is carried out, for example, by developing new indicators or tailoring the already existing ones, including factors considered important in the analysis. However, the presence of capable figures is required to develop these typologies of metrics.

Moreover, the database requires continuous updates to include either new indicators or modify the ones already in. Drivers of the changes can be internal to the company, such as objectives to be achieved, capabilities available or needs to be satisfied; or external, such as new environmental, economic or social criticalities that can emerge and need to be considered in strategic analysis and goals to achieve,

A second limitation of the study regards the scope of analysis. Table 6, i.e., the output presented to answer the first research question, also includes indicators for packaging products; while the analysis and the resulting framework limit their scope to KPIs related to organic goods. A parallel discussion could also be conducted for this aspect, both by maintaining the same analysis dimensions (TBL, CE strategies and level), and by including other factors, such as the specific stages of the supply chain in which the product underwent packaging processes. Decision-makers can also benefit from the creation of another framework to select the best indicators from the dashboard, following the process adopted to create the one presented in this study.

The last major limitation regards the boundaries of the study. Achieving a more sustainable future must not only concern companies and the decisions they make internally but, in an important sector such as the food sector, consumers must also be involved. Circularity approaches generate advantages for tackling food waste and loss only if they are supported by responsible consumption. The challenge of also impacting costumers' behaviours, which are out of the scope of companies, has to be faced. The challenges would not only concern the strategies to be implemented but above all the control that must be carried out to analyse the trends and results. Social dimension is the first approach to influence people and their behaviours, but activities aimed at their involvement must be continuously promoted.

Surely, companies operating in this challenging sector must be the first to adopt a responsible attitude towards pursuing a sustainable future in order to be a model not only for consumers but also for other sectors and thus achieve positive results.

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A. Appendix A

	Title	Authors	Year	Source title
1	Towards an interdisciplinary framework for effective sustainability assessment in manufacturing	Kumar M., Mani M.	2021	Procedia CIRP
2	Sustainability assessment in circular inter-firm networks: An integrated framework of industrial ecology and circular supply chain management approaches	Walker A.M., Vermeulen W.J.V., Simboli A., Raggi A.	2021	Journal of Cleaner Production
3	Closing the Loop for Packaging: Finding a Framework to Operationalize Circular Economy Strategies	Niero M., Hauschild M.Z.	2017	Procedia CIRP
4	A systematic literature review exploring uncertainty management and sustainability outcomes in circular supply chains	De Lima F.A., Seuring S., Sauer P.C.	2021	International Journal of Production Research
5	A procedure to support systematic selection of leading indicators for sustainability performance measurement of circular economy initiatives	Kravchenko M., Pigosso D.C.A., McAloone T.C.	2020	Sustainability (Switzerland)
6	Comparing life cycle impact assessment, circularity and sustainability indicators for sustainable design: Results from a hands-on project with 87 engineering students	Saidani M., Kravchenko M., Cluzel F., Pigosso D., Leroy Y., Kim H.	2021	Proceedings of the Design Society
7	Development of a biorefinery approach for shrimp processing in North-Colombia: Process simulation and sustainability assessment	Moreno-Sader K.A., Martinez-Consuegra J.D., González-Delgado Á.D.	2021	Environmental Technology and Innovation
8	Development of indicators for the sustainability of the sugar industry	García-Bustamante C.A., Aguilar-Rivera N., Zepeda-Pirrón M., Armendáriz-Arnez C.	2018	Environmental and Socio-Economic Studies
9	Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments	De Oliveira C.T., Dantas T.E.T., Soares S.R.	2021	Sustainable Production and Consumption
10	Life cycle sustainability assessment: Lessons learned from case studies	Alejandrino C., Mercante I., Bovea M.D.	2021	Environmental Impact Assessment Review
11	A case study approach to introduce circular economy in sustainable design education	Esparragoza I., Mesa-Cogollo J.	2019	Proceedings of the 21st International Conference on Engineering and Product Design Education: Towards a New Innovation Landscape, E and PDE 2019
12	Remanufacturing sustainability indicators: An Indonesian small and medium enterprise case study	Fatimah Y.A., Aman M.	2018	IOP Conference Series: Materials Science and Engineering
13	Capital-based life cycle sustainability assessment: Evaluation of potential industrial symbiosis synergies	Subramanian K., Chopra S.S., Ashton W.S.	2021	Journal of Industrial Ecology

	Title	Authors	Year	Source title
14	Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators	Kravchenko M., Pigosso D.C., McAloone T.C.	2019	Journal of Cleaner Production
15	Sustainability Performance Management Framework for Circular Economy Implementation in State-Owned Plantation Enterprises	Trisyulianti E., Prihartono B., Andriani M., Suryadi K.	2022	Sustainability (Switzerland)
16	Developing a set of sustainability indicators for product families based on the circular economy model	Mesa J., Esparragoza I., Maury H.	2018	Journal of Cleaner Production
17	The Proposal of an Environmental Break-Even Point as Assessment Method of Product-Service Systems for Circular Economy	Barletta I., Despeisse M., Johansson B.	2018	Procedia CIRP
18	Assessing the social sustainability of circular economy practices: Industry perspectives from Italy and the Netherlands	Walker A.M., Opferkuch K., Roos Lindgreen E., Simboli A., Vermeulen W.J.V., Raggi A.	2021	Sustainable Production and Consumption
19	Exploring assessment practices of companies actively engaged with circular economy	Roos Lindgreen E., Opferkuch K., Walker A.M., Salomone R., Reyes T., Raggi A., Simboli A., Vermeulen W.J.V., Caeiro S.	2022	Business Strategy and the Environment
20	Circular Economy indicators for supply chains: A systematic literature review	Calzolari T., Genovese A., Brint A.	2022	Environmental and Sustainability Indicators
21	An economic model of circular supply network dynamics: Toward an understanding of performance measurement in the context of multiple stakeholders	Brown P.J., Bajada C.	2018	Business Strategy and the Environment
22	Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review	Iacovidou E., Velis C.A., Purnell P., Zwirner O., Brown A., Hahladakis J., Millward-Hopkins J., Williams P.T.	2017	Journal of Cleaner Production
23	A critical review of academic approaches, methods and tools to assess circular economy at the micro level	Lindgreen E.R., Salomone R., Reyes T.	2020	Sustainability (Switzerland)
24	Sustainable agri-food processes and circular economy pathways in a life cycle perspective: State of the art of applicative research	Stillitano T., Spada E., Iofrida N., Falcone G., De Luca A.I.	2021	Sustainability (Switzerland)
25	Material flow analysis and sustainability of the Italian meat industry	Amicarelli V., Rana R., Lombardi M., Bux C.	2021	Journal of Cleaner Production
26	A trade-off navigation framework as a decision support for conflicting sustainability indicators within circular economy implementation in the manufacturing industry	Kravchenko M., Pigosso D.C.A., McAloone T.C.	2021	Sustainability (Switzerland)
27	Assessing the sustainability of urban eco-systems through Emergy-based circular economy indicators	Santagata R., Zucaro A., Viglia S., Ripa M., Tian X., Ulgiati S.	2020	Ecological Indicators
28	A social panorama within the life cycle thinking and the circular economy: a literature review	Mesa Alvarez C., Ligthart T.	2021	International Journal of Life Cycle Assessment
29	Measuring circular economy strategies through index methods: a critical analysis	Elia V., Gnoni M.G., Tornese F.	2017	Journal of Cleaner Production
30	The Regenerative Supply Chain: a Framework for Developing Circular Economy Indicators	Howard M., Hopkinson P., Miemczyk J.	2019	International Journal of Production Research
31	A taxonomy of circular economy indicators	Saidani M., Yannou B., Leroy Y., Cluzel F., Kendall A.	2019	Journal of Cleaner Production

	Title	Authors	Year	Source title
32	Circular economy performance assessment methods: a systematic literature review	Sassanelli C., Rosa P., Rocca R., Terzi S.	2019	Journal of Cleaner Production
33	How to monitor environmental pressures of a circular economy: an assessment of indicators	Helander H., Petit-Boix A., Leipold S., Bringezu S.	2019	Journal of Industrial Ecology
34	Circular economy metrics: literature review and company-level classification framework	Vinante C., Sacco P., Orzes G., Borgianni Y.	2021	Journal of Cleaner Production
35	A systematic review for measuring circular economy: the 61 indicators	De Pascale A., Arbolino R., Szopik-Depczynska K, Limosani M., Ioppolo G.	2020	Journal of Cleaner Production
36	Social circular economy indicators: selection through fuzzi Delphi method	Padilla-Rivera A., Do Carmo B.B.T., Arcese G., Merveille N.	2021	Sustainable Production and Consumption
37	Indicators in social life cycle assessment: a review of frameworks, theories, and empirical evidence	Kühnen M., Hahn R.	2017	Journal of Industrial Ecology
38	How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework	Saidani M., Yannou B., Leroy Y., Cluzel F.	2017	Recycling
39	Proposal of a Sustainable Circular Index for Manufacturing Companies	Azevedo S., Godina R., Matias J.	2017	Resources
40	Multi-method simulation-based tool to evaluate economic and environmental performance of circular product systems	Asif F.M.A., Lieder M., Rashid A.	2016	Journal of Cleaner Production
41	A robust Indicator for Promoting Circular Economy through Recycling	Di Maio F., Rem P.C.	2015	Journal of Environmental Protection
42	Circular economy in corporate sustainability strategies: A review of corporate sustainability reports in the fast-moving consumer goods sector	Stewart R., Niero M.	2018	Business Strategy and the Environment
43	Application of life cycle assessment in agricultural circular economy	Zhang X., Ma F., Wang L.	2013	Applied Mechanics and Materials
44	Circular Economy: measuring innovation in the product chain - policy report	Potting J., Hekkert M., Worrell E., Hanemaaijer A.	2017	PBL Netherlands Environmental Assessment Agency
45	Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics	Potting J., Hekkert M., Worrell E., Hanemaaijer A.	2019	Conservation and Recycling
46	Combining 5 criteria to identify relevant products measures for resource efficiency of an energy using products	Ardente F., Mathieux F., Recchioni M.	2013	Re-engineering Manufacturing for Sustainability
47	Circularity indicators, an approach to measure circularity	Ellen McArthur Foundation, ANSYS Granta	2019	
48	Design of indicators for measuring product performance in the Circular Economy	Cayzer S., Griffiths P., Beghetto V.	2017	International Journal of Sustainable Engineering
49	A review of micro level indicators for a circular economy - moving away from the three dimensions of sustainability	Kristensen, H.S.; Mosgaard, M.a.	2020	Journal of Cleaner Production
50	Circular economy indicators: what do they measure?	Moraga, G.; Huysveld, S; e altri	2019	Methodologies
51	The emergence of circular economy—A new framing around prolonging resource productivity.	Blomsma, F.; Brennan, G.	2017	Journal of Industrial Ecology

	Title	Authors	Year	Source title
52	Sustainability criteria and sustainability compliance index for decision support in product development	Hallstedt, S.I.;	2017	Journal of Cleaner Production
53	Sustainability assessment and indicators: Tools in a decision-making strategy for sustainable development	Waas, T.; Hugé, J.; Block, T.; Wright, T.; Benitez-Capistros, F.; Verbruggen, A.	2014	Sustainability
54	Evaluating the transition to the circular economy in the agri-food sector: Selection of indicators	Poponi S., Arcese G., Pacchera F., Martucci O.	2022	Resources, Conservation and Recycling
55	A systemic framework for sustainability assessment	Serenella Sala, Biagio Ciuffo, Peter Nijkamp	2015	Ecological Economics
56	A quantitative and holistic circular economy assessment framework at the micro level	Baratsas S. G., Pistikopoulos E. N., Avraamidou S.	2022	Computers & Chemical Engineering
57	Review of Emergy Analysis and Life Cycle Assessment: Coupling Development Perspective	Qingsong Wang, Hongkun Xiao, Qiao Ma, Xueliang Yuan, Jian Zuo, Jian Zhang, Shuguang Wang and Mansen Wang	2020	Sustainability
58	Measuring the circular economy-A Multiple Correspondence Analysis of 63 metrics	Parchomenko A., Nelen D., Gillabel J., Rechberger H.	2019	Journal of Cleaner Production
59	Leading product-related environmental performance indicators: a selection guide and database	Issa I., Pigosso D., McAloone T., Rozenfeld H.,	2015	Journal of Cleaner Production
60	An approach for estimating the end-of-life product disassembly effort and cost	Das S., Yedlarajiah P., Narendra R.	2000	International Journal of Production Research
61	GRI Standards Refernce Sheet		2021	
62	Framework to Evaluate the Performance of a New Industrial Business Model	Watanabe E.H., da Silva R.M., Tsuzuki M.S.G., Junqueira F., dos Santos Filho D.J., Miyagi P.E.	2016	IFAC-PapersOnLine
63	OECD Sustainable Manufacturing Toolkit, http://www.oecd.org/innovation/green/toolkit/oecdsustainablemanufacturingindicators.html			
64	Priority Evaluation of Product Metrics for Sustainable Manufacturing	Gupta A., Vangari R.,Jayal A.D., Jawahir I.S.	2011	Springer-Verlag Berlin Heidelberg, 2011
65	An investigation of indicators for measuring sustainable manufacturing	Chengcheng F., Carrell J. D., Zhang H.	2010	IEEE International Symposium on Sustainable Systems and Technology
66	An analysis of indicators disclosed in corporate sustainability reports	Roca L. C. and Searcy, C.	2012	Journal of Cleaner Production

B. Appendix B

The table is shown in the next page.

		Env	Soc	Eco	Red	Reu	Rcy	Rco	Nan	Micr	Mes	Mac
AIR	1	X			X					X		X
	2	X			X		X			X		X
	3	X			X		X		X			
	4	X			X							
	5	X			X					X		
	6	X			X					X		X
	7	X			X					X		X
	8	X			X					X		
	9	X			X	X				X	X	X
	10	X			X	X				X	X	
	11	X			X	X	X	X		X	X	
	12	X			X	X		X		X	X	
	13	X			X	X				X	X	
WATER	14	X			X		X	X		X		X
	15	X			X		X	X		X		X
	16	X			X					X		X
	17	X			X		X		X			
	18	X			X	X	X			X		
	19	X			X				X			
	20	X			X		X	X		X		X
	21	X			X	X	X			X		X
	22	X			X					X		
	23	X			X					X		
	24	X				X	X		X	X		
	25	X			X				X	X		
	26	X			X	X	X		X	X		
	27	X			X	X	X		X	X		
	28	X			X	X	X		X	X		X
	29	X			X							X
	30	X			X							X
	31	X				X				X		
	32	X			X					X		
SOIL	33	X			X				X	X		X
	34	X			X					X		X
	35	X			X					X		X
	36	X			X			X		X		X
	37	X			X							X
	38	X			X					X		X
	39	X			X					X		X
	40	X			X					X		X
ENERGY	41	X			X		X			X		X
	42	X			X		X			X		X
	43	X			X		X			X		X
	44	X			X		X			X		X
	45	X			X					X		X
	46	X			X			X				
	47	X			X			X				
	48	X			X			X		X		X
	49	X			X					X		X
	50	X			X				X			X
	51	X			X				X			
	52	X			X				X			
	53	X			X				X			
	54	X			X				X			
	55	X			X					X		
	56	X			X		X		X			
	57	X			X		X		X			
TRANSPORT	92	X			X	X					X	
	93	X			X	X	X	X		X	X	
	94	X			X	X	X	X		X	X	
	95	X			X	X	X	X			X	X
	96	X			X					X	X	X
	97	X		X	X					X	X	

		Env	Soc	Eco	Red	Reu	Rcy	Rco	Nan	Micr	Mes	Mac
SOCIAL	98		X		X						X	
	99		X		X		X	X			X	
	100		X		X	X	X	X			X	X
	101		X		X	X	X	X			X	X
	102		X		X	X					X	X
	103		X		X	X	X	X			X	X
	104		X		X						X	
	105		X		X	X	X	X			X	X
	106		X		X	X	X	X			X	
	107		X		X	X	X	X			X	
REVENUES	108			X		X			X	X		
	109			X		X	X		X			
	110			X	X				X	X		
	111			X	X				X	X		
COSTS	112			X	X					X		
	113			X	X				X			
	114			X	X					X		
	115			X	X				X			
	116			X	X				X	X		
	117			X	X					X		
	118			X	X					X		
	119			X	X				X			
	120			X	X				X	X		
	121			X	X	X	X	X	X	X	X	
	122			X	X					X		
	123			X	X					X		
	124			X	X					X		
	125			X	X					X		
	126			X	X					X		
	127			X	X					X		
	128			X	X					X		
	129			X	X					X		
	130			X			X		X	X		
	131			X	X	X					X	
	132	X		X	X					X		
	133	X		X	X					X		
	134	X		X	X		X			X		
	135	X		X	X	X	X	X		X		
	136	X		X	X	X	X	X		X	X	
	137			X	X				X			
	138		X	X	X					X		
	139		X	X	X					X		
EFFICIENCY AND PRODUCTIVITY	140			X		X				X		
	141			X	X				X	X		
	142	X			X							X
	143	X			X							X
	144	X			X							X
	145			X	X							X
	146			X	X							X
	147			X	X	X	X	X		X		
	148			X	X	X	X		X	X		
	149			X	X	X	X		X	X		X
	150			X		X				X		
	151			X			X			X		
	152	X		X		X			X			
	153	X		X			X		X			
	154	X		X				X	X			
	155	X	X	X			X		X	X		
	156	X		X	X	X	X	X	X	X		
	157	X			X		X			X		
	158	X				X			X	X		
	159	X					X		X			
	160	X				X	X		X			
	161	X					X		X			
	162	X					X	X	X			
	163	X						X	X	X		

		Env	Soc	Eco	Red	Reu	Rcy	Rco	Nan	Micr	Mes	Mac
MATERIAL AND RESOURCE CONSUMPTION	58	X			X		X	X		X		
	59	X			X					X		
	60	X			X					X		X
	61	X			X					X		X
	62	X			X					X		
	63	X					X			X		
	64	X	X		X				X	X		
	65	X	X		X	X	X	X	X	X		
	66	X	X		X	X	X	X	X	X		
	67	X	X		X				X	X	X	
	68	X					X		X	X		
	69	X				X				X		
	70	X					X			X		
	71	X			X		X		X	X		
	72	X					X			X		
	73	X					X			X		
	74	X			X		X			X		
	75	X			X					X		

		Env	Soc	Eco	Red	Reu	Rcy	Rco	Nan	Micr	Mes	Mac
WASTE	76	X			X	X	X		X			
	77	X			X		X		X	X		
	78	X			X				X	X		
	79	X			X					X		
	80	X			X				X			
	81	X			X					X		
	82	X			X		X			X		
	83	X			X				X			
	84	X			X		X		X			
	85	X			X		X	X		X		X
	86	X			X		X	X		X		X
	87	X			X		X	X		X		X
	88	X			X		X	X		X		X
	89	X			X		X	X	X			
	90	X			X		X	X		X		X
	91	X			X	X	X			X		

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