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APPLICATION OF AN INNOVATIVE METHODOLOGY FOR EVALUATING THE CIRCULARITY AND THE ENVIRONMENTAL IMPACTS OF AGRI-FOOD PRODUCTS

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Abstract

Resource scarcity and the problem of waste management are two of the key issues in contemporary society that encourage reflection on the benefits of transitioning to a Circular Economy (CE) model. CE is defined by the Ellen MacArthur Foundation (EMF) as a global economic model that decouples economic growth and development from the consumption of finite resources. Bioeconomy (BE), the socioeconomic system that encompasses and interconnects economic activities that use renewable bioresources from the soil and sea (also called biobased resources) to produce food, materials, and energy, represents a fundamental variation of CE as one of its developing areas. In this framework, BE as a means of reducing environmental impact is found to be central to international policies. The CE monitoring process through specific measurement tools (i.e., with respect to material consumption and environmental impacts) is an open field of research whose importance is also outlined in the European CE Action Plan. Furthermore, literature studies show that there are no case studies applied to current integration models to assess whether circularity (both in terms of biological and technical cycles according to the EMF methodology) means reducing environmental impacts. The purpose of this research is firstly to propose an approach in which to apply the most recognized circular and environmental measurement tools so that to correlate circularity with environmental impacts. Secondly, it is to test and analyze the model through compared case studies and assess its applicability as an effective product circularity-environmental assessment tool which indicates whether applying circular principles can improve or worsen the environmental impacts of products.

To facilitate the choice of the most appropriate assessment methods for this purpose, several systematic literature reviews are performed. Firstly, a quali-quantitative assessment of several indicators to measure circular and environmental performances of products is completed whose results led to the Material Circularity Indicator (MCI) by the EMF as the most cited circular economy and bioeconomy indicator, and the Life Cycle Assessment (LCA) as the most suitable environmental impacts assessment tool within bioeconomy. Secondly, several literature integration/combination patterns between circularity and environmental assessments are detected which lead to a non-univocal consensus and to evaluations not yet consolidated.

To address the research needs, a MCI-LCA methodological integration model is proposed in which compared case studies are selected in the agri-food sector (since their products encompass both biological and technical materials) to test and analyze the model. As a result, an innovative circular and environmental assessment panel of coupled products belonging to the same product category is implemented. Specifically, five scenarios are detected in which the relationship between circularity and the relative environmental impacts varies according to the trend line slope linking the product analyzed to another comparable product. Compared to studies in the current literature, the added value of the application of the MCI-LCA integrated model is to allow for a comprehensive and holistic assessment through an innovative circular (both in terms of biological and technical cycles) and environmental assessment panel of coupled products (and the relative scenarios) belonging to the same product category.

As a general outcome, applying the principles of CE do not always mean reducing the environmental impact, as it depends on the type of impact category and product. The results achieved through the application of the principles of the proposed MCI-LCA integrated model make the latter validated by improving the scientific awareness on circularity and environmental impacts associated with it and linking the circular-environmental framework to suitable mitigation measures. Still, there is room for improvement: the lifetime, the recycling rate, and the circular biological cycles assumptions affect the validity; all MCI results are highly dependent on how the system boundary is defined, and the presence of rebound effects; the results are also affected by the definition of the linear scenario. A further limitation of the method is the insufficient amount of case studies that tested the viability of the proposed scenarios. Also, additional compared case studies are required to be applied to the proposed integrated model for several other reasons. Firstly, to strengthen the assumption of equivalence between sustained biological feedstock and primary biological raw materials of organic products. Secondly, to determine if eventual adjustments to the weighing system of technical and biological cycles are required. Ultimately, for the detected circular-environmental scenarios to be considered as general or sector guidelines for the integrated circular-environmental assessment of products and try to bridge the gap of standardized regulations on CE measurement framework, which has led to the current nonuniform indicator approaches.

Riassunto

La carenza di risorse ed il problema della gestione dei rifiuti sono due dei temi chiave della società contemporanea che incoraggiano a riflettere sui benefici della transizione verso un modello di circular economy (CE). La CE è definita dalla Ellen MacArthur Foundation (EMF) come un modello economico globale che separa la crescita economica e lo sviluppo dal consumo di risorse non rinnovabili. La bioeconomy (BE), ovvero il sistema socioeconomico che comprende e interconnette le attività economiche che utilizzano biorisorse rinnovabili dal suolo e dal mare (chiamate anche risorse biobased) per produrre cibo, materiali ed energia, rappresenta una variazione fondamentale della CE in una delle sue aree in via di sviluppo. In questo contesto, la BE come mezzo per ridurre l'impatto ambientale è considerata centrale per le politiche internazionali. Il processo di monitoraggio della CE attraverso specifici strumenti di misurazione (ovvero rispetto al consumo di materiali e agli impatti ambientali) è un campo di ricerca aperto la cui importanza è delineata anche nel Piano d'Azione europeo per la CE. Inoltre, degli studi di letteratura dimostrano che non esistono casi di studio applicati agli attuali modelli di integrazione per valutare se la circolarità (sia in termini di cicli biologici che tecnici secondo la metodologia EMF) significhi ridurre gli impatti ambientali. Lo scopo di questa ricerca è in primo luogo quello di proporre un approccio in cui applicare i più riconosciuti strumenti di misurazione circolare ed ambientale in modo da correlare la circolarità con gli impatti ambientali. In secondo luogo, è quello di testare ed analizzare il modello proposto attraverso dei casi di studio comparati e valutarne l'applicabilità come strumento efficace di valutazione circolare-ambientale di prodotto che indichi se l'applicazione di principi circolari può migliorare o peggiorare gli impatti ambientali di prodotto.

Per facilitare la scelta dei metodi di valutazione più appropriati per questo scopo, vengono eseguite diverse revisioni sistematiche di letteratura. In primo luogo, viene completata una valutazione quali-quantitativa di diversi indicatori circolari ed ambientali di prodotto i cui risultati hanno portato al Material Circularity Indicator (MCI) sviluppato da parte dell'EMF come indicatore di CE e BE più citato, ed al Life Cycle Assessment (LCA) come strumento di valutazione degli impatti ambientali più adatto in ambito di BE. In secondo luogo, dalla letteratura vengono rilevati diversi modelli di integrazione/combinazione tra circolarità e valutazioni ambientali che portano ad un consenso non univoco ed a valutazioni non ancora consolidate.

Per rispondere alle esigenze di ricerca, viene proposto un modello di integrazione metodologica tra MCI e LCA in cui vengono selezionati dei casi di studio comparati nel settore agroalimentare (poiché i loro prodotti comprendono sia materiali biologici che tecnici) per testare ed analizzare il modello. Come risultato, viene implementato un innovativo pannello di valutazione circolare ed ambientale di prodotti accoppiati appartenenti alla stessa categoria merceologica. Nello specifico, vengono rilevati cinque scenari in cui la relazione tra circolarità e relativi impatti ambientali varia a seconda della pendenza della linea di tendenza che collega il prodotto analizzato ad un altro prodotto comparabile. Rispetto agli studi presenti in letteratura, il valore aggiunto dell'applicazione del modello integrato MCI-LCA è quello di consentire una valutazione completa ed olistica

attraverso un innovativo pannello di valutazione circolare (sia in termini di cicli biologici che tecnici) ed ambientale dei prodotti accoppiati (e dei relativi scenari) appartenenti alla stessa categoria merceologica.

Come indicazione generale, applicare i principi della CE non significa ridurre l'impatto ambientale in quanto ciò dipende dal tipo di categoria di impatto e dal prodotto analizzato. I risultati raggiunti attraverso l'applicazione dei principi del modello integrato MCI-LCA proposto lo validano migliorando la consapevolezza scientifica sulla circolarità e sugli impatti ambientali ad essa associati, e collegando il quadro circolare-ambientale sviluppato ad idonee misure di mitigazione. Tuttavia, sono presenti margini di miglioramento: la durata, il tasso di riciclaggio e le assunzioni relative ai cicli biologici circolari influenzano la validità del modello; tutti i risultati di MCI dipendono fortemente da come vengono definiti i confini del sistema e dalla presenza di rebound effects; i risultati sono influenzati altresì dalla definizione degli scenari lineari. Un'ulteriore limitazione del metodo è l'insufficiente quantità di casi di studio che hanno testato la validità degli scenari proposti. Inoltre, sono necessari ulteriori casi di studio comparati da applicare al modello integrato proposto per diversi altri motivi. In primo luogo, per rafforzare l'assunzione di equivalenza tra feedstock biologico da produzione sostenuta e materie prime biologiche primarie di prodotti organic. In secondo luogo, per determinare se sono necessari eventuali adeguamenti al sistema di pesatura dei cicli tecnici e biologici. In definitiva, per considerare gli scenari circolari-ambientali rilevati come linee guida generali o settoriali per la valutazione integrata circolare-ambientale di prodotto e cercare di colmare il gap delle normative standardizzate sul quadro di misurazione della CE che ha portato all'attuale non uniformità nei metodi di indicatori.

List of publications

1. Gallo, F., Manzardo, A., Camana, D., Scipioni A. (2021) Circular Bioeconomy metrics and Life Cycle Assessment. Answers from literature review. Italian LCA Network 15th Annual Meeting - Abstract Book. ISBN: 9791221004564.

2. Gallo, F., Manzardo, A., Camana, D., Scipioni A. (2022) Integration of Circular Economy metrics with Environmental Impact Assessment: methodological proposal. Italian LCA Network 16th Annual Meeting - Abstract Book. ISBN: 9791221004588.

3. Gallo, F., Manzardo, A., Camana, D., Fedele A., Scipioni A. (2023) Integration of a circular economy metric with Life Cycle Assessment: methodological proposal of compared agri-food products. The International Journal of Life Cycle Assessment. doi: 10.1007/s11367-022-02130-0.

List of abbreviations

ADP-E	Abiotic Depletion Potential-Elements
ADP-FF	Abiotic Depletion Potential-Fossil Fuels
AP	Acidification Potential
BE	BioEconomy
BoM	Bill of Materials
C	Core processes
CA	Circular Assessment
CE	Circular Economy
D	Downstream processes
EA	Environment Assessment
EMF	Ellen MacArthur Foundation
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EU	European Union
F(X)	Utility Function
GPI	General Programme Instructions
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFI	Linear Flow Index
M	Product material flow
MCI	Material Circularity Indicator
NON-ORG	Product non-organic version

ORG	Product organic version
PCR	Product Category Rules
POFP	Photochemical Oxidation Formation Potential
S	Trend line slope
U	Upstream processes
V	Product virgin raw material
W	Product unrecoverable waste
WSF	Water Scarcity Footprint

Contents

1 Introduction

Sustainability was defined as development that meets the needs of the present generation without compromising the ability of future generations to meet their needs (WCED, 1987). Nowadays it seems to be essential to address growing concerns about the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development. Sustainable development requires an integrated approach that takes into account environmental concerns along with economic development (UN, 2023), and the circular economy is internationally recognised as a reliable solution. CE is a new and inclusive economic paradigm that aims to minimize pollution and waste, extend product lifecycles, and enable broad sharing of physical and natural assets. It strives for a competitive economy that creates green and decent jobs and keeps resource use within planetary boundaries (UNECE, 2023). At the product level, studies in the literature have shown that there are no case studies that demonstrate a clear correlation between the application of CE principles and the relative reduction of environmental impacts. This thesis contributes to empower the scientific knowledge about circular economy and bioeconomy strategies to explore their effects on several environmental impact categories.

This chapter illustrates the urgency of circularity approaches and the unclear patterns between the latter and environmental impacts associated with it (Section 1.1). Further, the thesis' focus on the integrated assessment on circularity and environmental impacts of products is outlined and the structure of the thesisis illustrated (Section 1.2).

1.1 Background and Motivation

1.1.1 Circular Economy and Bioeconomy as flywheels for sustainable growth

Sustainability characterizes an orientation in which it is necessary to simultaneously address the three crises that have defined the current world for more than twenty years, which are the economic, social, and environmental crises. The challenge is to find a development model oriented to the simultaneous overcoming of all these crises. The aim of sustainability is to ensure that the needs of present generations are met without compromising the ability of future generations to meet their own needs (WCED, 1987).

The CE is a concrete way to understand what sustainability entails from the point of view of the processes of the economic system, i.e., its change from a linear to a circular logic. The linear economy model foresees unlimited use of resources and involves the acceleration of phenomena (i.e., loss of biodiversity and entire ecosystems; pollution; increase in natural resources not supported by increased biocapacity; greater volatility and higher prices for raw materials and natural resources). In the CE model, companies, to cope with the risks outlined above, change the current business to make their activities less and less dependent on natural resources and raw materials. The production processes and the materials used must be assimilated to the natural elements and therefore be able to regenerate. CE lets the use of waste of a product as a new input to create productivity and income. CE is defined by the Ellen MacArthur Foundation (EMF, 2019) as a global economic model that decouples economic growth and development from the consumption of finite resources. The CE proposes approaches of dematerialization, i.e., the management of everything that is not necessary to be material through digital technologies, new logics of product as a service where the responsibility of the product remains with the producer who can optimize all processes related to CE, and industrial symbiosis for the organization and coordination of all companies interested in the circular optimization of their processes/products.

International politics is paving the way to CE. The 2030 Agenda is the global policy tool for the current decade that directs towards seventeen specific integrated sustainability goals of the United Nations of a social, economic, and environmental nature. Goal no. 12 relates to responsible consumption and production. The European Green Deal also goes in this direction through several lines of action concerning the CE (Circular Economy Action Plan), biodiversity (The EU Biodiversity Strategy for 2030) and the food sector (Farm to Fork Strategy). At the Italian level, the PNRR (National Recovery and Resilience Plan) provides for investments of 221 billion euros, of which 68.6 billion in CE, in order to improve the sustainability and resilience of the country and the economic system. One of the objectives of the Plan is to improve the Italian supply chain in the agricultural and food sectors. The PNRR plans investments in bioeconomy (BE) for 5.27 billion euros, in order, together with other objectives, to develop a smart and sustainable agricultural/food supply chain reducing its environmental impact through "green" supply chains. This action aims to improve the competitiveness of farms and their climate-environmental performance, strengthening the sector's logistics infrastructure, reducing greenhouse gas emissions, and supporting the spread of precision agriculture and the modernization of machinery.

In this framework, where CE and BE as a means of reducing environmental impact were found to be central to international policies, reliable and applicable science-based methods and tools are necessary to measure the circularity performances of products and to assess their relationship with the environmental impacts associated with them.

1.1.2 Uncertain patterns between circularity and the environmental impacts associated with it

Just as a road sign helps drivers follow the correct direction to their desired destination, indicators condense a series of complex information to help understand in which direction – towards or far from the set objectives – the policies implemented are heading. However, when a series of information is combined in such a tool, special care must be taken to interpret it correctly. This is extremely valid in the case of indicators for measuring the CE and the associated environmental impacts that require monitoring in physical terms (mass and energy flows) of the environmental aspects of the systems examined. Therefore, the measurement of circularity through specific indicators is an essential requirement for policy implementation processes and the consequent achievement of concrete actions and measurable results in the transition to the CE. Measuring the progress of circularity policy will create the basis for identifying common objectives and the results of the monitoring will be the starting point for setting new priorities towards long-term goals.

Many CE indicators have been developed by different stakeholders with different scopes and applications (Saidani et al. 2019) to measure and assess the achievement of specific CE targets (Morseletto 2020). However, there is no prevailing opinion on the implementation feasibility of circularity indicators (de Oliveira et al. 2021) that should aim to improve the environmental performance of society (Harris et al. 2021). de Oliveira et al. (2021) underline the need to integrate CE indicators with methodologies that support environmental sustainability. The CE monitoring process through specific measurement tools (i.e., with respect to material consumption and environmental impacts) is an open field of research whose importance is also outlined in the European CE Action Plan (EUR-LEX 2020).

In recent years, there has been increasing theorization about the possibility of integration between the assessment of the environmental impacts of products/processes (generally indicated as environmental assessment – EA) and their levels of circularity (circularity assessment – CA). Declaring that integration is defined as the process of combining EA with CA (Mantalovas and Di Mino 2020), the current integration/combination models of the studies may be summarized into two models. Some authors applied the separate conduction model in which EA and CA are conducted separately, and independent results are combined with each other. The applications of such model were on washing machines (Bracquené et al. 2020), alkaline batteries (Glocic et al. 2020), tires (Lonca et al. 2018), food packaging (Pauer et al. 2019), PET bottles (Schmidt et al. 2020), anaerobic treatments of dairy processing effluents (Stanchev et al. 2020), and poultry production (Rocchi et al. 2021). Other authors focused on integrated conductions in which EA and CA are conducted separately, and independent results are combined together and joint in a single tool: Mantalovas and Di Mino (2020) focused on asphalt mixtures, Niero and Kalbar (2019) on beer packaging, and Rufí-Salìs (2021) on urban agriculture. Apart from understanding that circularity indicators do not seem to be suitable to be used alone (Rigamonti and Mancini 2021), both models lead to a non-univocal consensus and to evaluations not yet consolidated, which suggests a potential need for further investigation in alternative models.

1.2 Focus of the thesis

1.2.1 Integrated assessment of circularity and environmental impacts of products

The broad interest of international decision-makers for going towards circularity logics testified by several funding plans means that there is a fertile environment for achieving global sustainable growth. However, no case studies applied to current integration models to assess whether circularity (both in terms of biological and technical cycles according to the EMF methodology (2019)) means reducing environmental impacts. Haupt and Zschokke (2017) already stated that the most circular solution is not necessarily the most environmentally preferable option.

Based on the most recognized and effective circular and environmental measurement tools, the purpose of this thesis is firstly to propose an approach in which to apply the detected tools to correlate circularity with environmental impacts. Secondly, it is to test and analyze the model through compared case studies and assess its applicability as an effective product circularity-environmental assessment tool which indicates whether applying circular principles can improve or worsen the environmental impacts of products.

1.2.2 Aim and structure of the thesis

The outlined research needs are addressed within this thesis, which aims at assessing whether Circular Economy, and specifically Bioeconomy, reduce the environmental impact of products. After this introductory part (Chapter 1), the research questions and the research targets are specified (Chapter 2). Given the cumulative character of the thesis (i.e., the main results are object of included publications), also the linkage between each publication and the research targets is included in Section 2.2. The results, i.e. the publications, results summaries and eventual comments and results updates, are illustrated in Chapter 3. Chapter 4 provides an overall discussion of the performance and limitations of the MCI-LCA methodological integration model developed in the thesis (Section 4.1). Finally, Chapter 5 illustrates overall conclusions of the thesis and provides recommendations for future research.

2 Research Approach

This Chapter presents the research questions and the specific targets of the thesis (Section 2.1) and specifies how the publications address each target (Section 2.2). Figure 2.1 visualizes the research approach.

2.1 Research questions and research targets

Circularity faces several challenges in assessing its relationship with the environmental impacts associated with it. The aim of this thesis is to assess if Circular Economy, and specifically Bioeconomy, reduce the environmental impact of products. This purpose raises three overarching research questions (Q1, Q2 and Q3), specified by four related targets (T1.1-T3.2).
As a first step corresponding to the first research question, the state of the art is explored via a systematic analysis of existing approaches addressing the measurement of Circular Bioeconomy and the environmental impacts associated with it.

Q1 How do you measure Circular Bioeconomy and the environmental impacts associated with it?

Specifically, the focus is set on methods and tools as reliable metrics for the circular and environmental assessments of products.

T1.1 *Review of the state of the art of approaches addressing the measurement of Circular Bioeconomy and the environmental impacts associated with it*

The analysis of the literature integration/combination models between circularity and environmental metrics in order to understand their correlation is addressed in the second step of the thesis.

Q2 *Is there a relationship between measuring Circular Bioeconomy and environmental impacts?*

T2.1 Analysis of the literature integration/combination models between circularity and environmental assessments

The development of the circular-environmental integrated method and its application are addressed in the third and final step of the thesis:

Q3 *Is the circular-environmental assessment of products feasible and practically applicable?*

T3.1 Development of the MCI-LCA integrated method

T3.2 Application of the MCI-LCA integrated method in compared case studies

2.2 Linkage between publications, research targets, and research approach development

The three publications of the thesis pursue the targets illustrated in Section 2.1 and contribute to answer the research questions. This section addresses each publication's linkage to the targets and explains the development of the overall research methods (through several literature analyses and the framework of the proposed integrated model) and outcomes.

The 1. publication is a review of existing approaches and addresses T1.1.

1. Gallo, F., Manzardo, A., Camana, D., Scipioni A. (2021) Circular Bioeconomy metrics and Life Cycle Assessment. Answers from literature review. Italian LCA Network 15th Annual Meeting - Abstract Book. ISBN: 9791221004564.

The 1. publication's method of analysis consists of systemic literature review in which several combinations of keywords are inserted. The latter concern CE and circular BE topics along with multiple CE indicators to detect the most cited circularity measurement tool, while keywords on environmental impacts and measurement evaluation associated with the BE topic are entered to assess the most popular environmental impact measurement tool. The manuscript detects Material Circularity Indicator (MCI) and Life Cycle Assessment (LCA) as two reliable metrics by which measure Circular Bioeconomy and environmental impacts, respectively, thus providing the basis for identifying requirements and development needs for their integration/combination patterns.

The results pave the way for the further development of the thesis through the 2. publication.

2. Gallo, F., Manzardo, A., Camana, D., Scipioni A. (2022) Integration of Circular Economy metrics with Environmental Impact Assessment: methodological proposal. Italian LCA Network 16th Annual Meeting - Abstract Book. ISBN: 9791221004588.

The 2. publication provides the foundation for achieving T2.1 through a targeted literature analysis focused on applied circularity and environmental assessment models from which different integration/combination patterns are outlined. Plus, additional literature insights provide hints for an integration model between MCI and LCA are given beginning to address T3.1. The remaining part of T3.1 is fulfilled thanks to the 3. publication whose methods describe the development of a specific MCI-LCA methodological integration model with its phases, and the types of case studies. Specifically, the 3. publication keeps developing the MCI-LCA integrated method by using complementary indicators (calculated using the LCA methodology) together with the MCI through a Cartesian graph to obtain an in-depth analysis of the circular and environmental performance of the products.

3. Gallo, F., Manzardo, A., Camana, D., Fedele A., Scipioni A. (2023) Integration of a circular

economy metric with Life Cycle Assessment: methodological proposal of compared agri-food products. The International Journal of Life Cycle Assessment. doi: 10.1007/s11367-022-02130-0.

Compared case studies are selected in the agri-food sector since their products encompass both biological and technical materials and applied to the MCI-LCA integrated method to address T3.2. The paper allows a comprehensive and holistic assessment through an innovative circular and environmental assessment panel of coupled products belonging to the same product category. Specifically, five scenarios for the circular-environmental assessment of compared products are detected depending on the characteristics of the trend line which links the product analyzed to another comparable product.

This thesis is the result of a collaboration between the University of Padua and an environmental consulting and engineering private company that operates in the industrial waste treatment field (ECO-Management Srl, Monselice - Padua - Italy) within a particular doctorate category called "Apprendistato di alta formazione e ricerca". The agreement with Protocol No. 202332 dated 21/05/2019 aimed at providing a method to assess the environmental sustainability of innovative circularity models. A further company, Rigoni di Asiago Srl, contributed to the development of the doctoral research project thanks to one of its core products which served as a real case study (see T3.2).

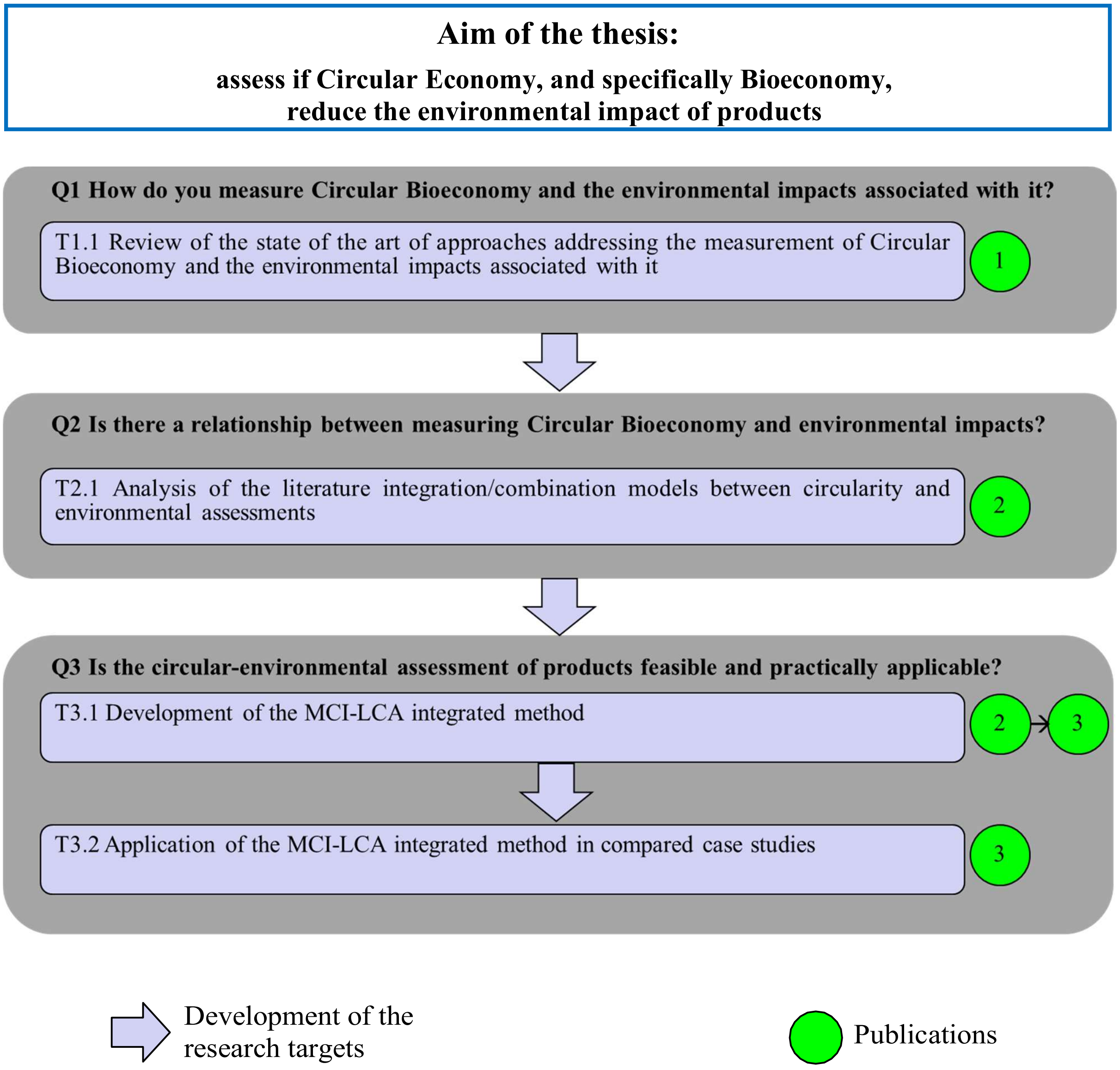

Figure 2.1: Research approach of the thesis: research questions, related targets, and publications

3 Results

This chapter presents the results of the thesis and is structured in three sections according to the research questions addressed in the included publications. Section 3.1 is dedicated to the review of and lessons learned from existing approaches that aim at measuring the Circular Bioeconomy and the environmental impacts associated with it. Section 3.2 presents the analysis of the literature integration/combination models between circularity and environmental assessments. Section 3.3 focuses on the development of the MCI-LCA integrated method and applies solutions to provide a circular-environmental assessment tool for products.

A summary of the results is provided before each publication. Eventual updates to the state of the art are presented after the related publication. An overarching discussion of the results can be found in Chapter 4.

3.1 Assessment of the circularity and environmental impacts measurement tools: gaps and challenges

3.1.1 Circular Bioeconomy metrics and Life Cycle Assessment. Answers from literature review

This publication provides a quali-quantitative assessment of several indicators to measure circular and environmental performances of products, respectively.

1. Gallo, F., Manzardo, A., Camana, D., Scipioni A. (2021) Circular Bioeconomy metrics and Life Cycle Assessment. Answers from literature review. Italian LCA Network 15th Annual Meeting - Abstract Book. ISBN: 9791221004564.

Results summary

The results of the systematic literature review completed to assess the most suitable circularity measurement tool led to the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation (EMF) which resulted as the most cited circular economy and bioeconomy indicator. From the systematic literature review completed to assess the most suitable environmental impacts assessment tool within bioeconomy, a subset of circular bioeconomy environmental impact papers is detected entering several keywords in which the 83% on average concerned the Life Cycle Assessment (LCA) tool. The scenario revealed of intense scientific activity suggests a potential need for further investigation in these tools. A possible future research opportunity could be represented by the comprehension whether the mentioned tools could be applied on an integrated approach, filling the knowledge gap about the coexistence of circularity and environmental sustainability.

Circular Bioeconomy metrics and Life Cycle Assessment. Answers from literature review

Federico Gallo[1], Alessandro Manzardo[1], Daniela Camana[1], Antonio Scipioni[1*]

Abstract: Resource scarcity and the problem of waste management are two of the key issues in contemporary society that encourages the reflection on the benefits of transitioning to a Circular Economy (CE) model. Bioeconomy, the socio-economic system that encompasses and interconnects economic activities that use renewable bio-resources of the soil and sea (also called bio-based resources) to produce food, materials and energy, represents a fundamental variation of the CE. In the analyzed context, where it is necessary moving towards CE and reducing the environmental impacts, a systematic literature review was conducted using different keywords combinations. Results show that Material Circularity Indicator (MCI) and Life Cycle Assessment (LCA) could be two reliable metrics by which measure Circular Bioeconomy and environmental impacts, respectively.

1. Introduction

The linear economy model foresees an unlimited use of resources and involves the acceleration of phenomena. In the Circular Economy (CE) model, companies, to cope with the risks outlined above, change the current business to make their activities less and less dependent on natural resources and raw materials. The production processes and the materials used must be assimilated to the natural elements and therefore be able to regenerate. CE let the use of waste of a product as a new input to create productivity and income. CE is defined by the Ellen MacArthur Foundation (EMF, 2019) as a global economic model that decouples economic growth and development from the consumption of finite resources.

In a "cyclical" system the waste concept does not exist, waste is referred to as potential materials to be transformed into new resources. With resource extraction and transformation leading to half of total greenhouse gas emissions and more than 90% of biodiversity loss and water stress, the European Green Deal has launched a concerted strategy for a climate-neutral, resource-efficient and competitive economy. According to the 2020 CE Action Plan of the European Commission, extending the CE from precursors to traditional economic operators will contribute significantly to achieving climate neutrality by 2050 and disassociating economic growth from the use of resources, while ensuring the EU's long-term competitiveness (EU, 2020). The mentioned decoupling is one of the strategies of the UN Sustainable Consumption and Production policies (UNEP, 2021) which push the production system to look at CE models to reduce its environmental impact.

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Bioeconomy (BE) represents a fundamental variation of the CE as one of its developing area. In addition to relying on renewable resources, BE feeds the "biological cycle" intended as the recovery and energy enhancement of organic waste deriving from waste production processes (MATTM and MISE, 2017). BE aims to ensuring food security, moving from a fossil-based economy to a bioeconomy and unlocking the potential of sea and oceans through better use of our resources and smart use of those we don't use yet (EU, 2015)

The 2018 EU Bioconomy Strategy aims to reduce the environmental impact with a three-tiered action plan which includes: strengthen and scale up the bio-based sectors, unlock investments and markets; deploy local bioeconomies rapidly across the whole of Europe; understand the ecological boundaries of the bioeconomy (EU, 2018). The consequences of this strategy come to fruition through several funding plans characterized as follows: 100 million € in the thematic investment platform for circular bioeconomy (EU, 2018); 3.85 billion € allocated under the EU Horizon 2020 funding programme ("Food security and sustainable use of biological resources") (EU, 2014); 10 billion € under Horizon Europe for **thematic clusters** including "Food, Bioeconomy, Natural Resources, Agriculture & Environment" for the period 2021-2027 (EUcalls, 2021).

Therefore, the stakeholders interest in the reduction of environmental impacts and, in particular, in the bioeconomy seem to be concrete. In order to measure and report its pattern, it is worth identifying values in the form of indicators. Many CE indicators have been developed by different stakeholders with different scopes and applications (Saidani et al., 2019). However, there is no prevailing opinion on their implementation feasibility (de Oliveira et al., 2021) which should be aimed to improve environmental performance of society (Harris et al., 2020). De Oliveira et al. (2021) underline the need of integrating CE indicators with methodologies supporting environmental sustainability. The CE monitoring process thorough specific measurement tools (i.e. regarding material consumption and environmental impacts) is an open field of research whose importance is outlined also in the European CE Action Plan (EU, 2020).

2. Research methodology

2.1. Research questions

In the context described above, where it is necessary moving towards CE and environmental impacts reduction, BE is considered as one of the CE developing areas, and no consensus has been reached about circular and environmental impacts metrics, the research questions shown in Tab. 1 have emerged. Details on research design are provided in section 2.2.

Tab. 1: Research topic

N.	Research Question	Section	Method of analysis
1	How do you measure Circular Bioeconomy?	3.1	Systematic literature review and discussion of results
2	How do you measure environmental impacts within Bioeconomy?	3.2	

2.2. Method of analysis

The schemes of the material collection for the analysis based on a systematic approach are shownin Tab. 2 and Tab. 3. Two major scientific databases, Web of Science and Scopus, were chosen as fonts. Keywords were selected in order to be more wide-ranging as possible, considering 3 groups linked by the operator AND for both Questions mentioned in Tab. 1.

Tab. 2: Material collection process for Question 1

Database search – Web of Science and Scopus (31/08/2020)		
Focus of analysis	Keywords inserted in "Title, abstract or author-specified keywords" for Web of Science and "Article title, Abstract, Keywords" for Scopus	
Circular Economy	AND	"Circular Economy"
Circular Economy Indicator	AND	"Material Circularity Indicator" OR "Resource Productivity" OR "End-of-Life Recycling Rates" OR "Circularity Index" OR "Circular Economy Index" OR "Economy-Wide Material Flow Analysis" OR "Hybrid LCA Model" OR "Zero Waste index" OR "Reuse Potential Indicator" OR "Circular Economy Toolkit" OR "Product-Level Circularity Metric" OR "Recycling Rates" OR "Circular Economy Indicator Prototype" OR "Circular Economy Performance Indicator" OR "National Circular Economy Indicator System" OR "Value-based Resource Efficiency" OR "Circular Economy Monitoring Framework" OR "Eco-efficient Value Ratio" OR "Sustainable Circular Index" OR "Building Circularity Indicators" OR "Circularity Assessment Tool" OR "Circular Economic Value" OR "Evaluation of Regional Circular Economy" OR "EU Resource Efficiency Scoreboard" OR "Circle Assessment" OR "Circularity Calculator" OR "Circularity Material Cycles" OR "Circularity Potential Indicator" OR "Evaluation Indicator System of Circular Economy" OR "Material Reutilization Part" OR "Environmental Protection Indicators (EPICE) in a context of CE" OR "Circularity Indicator Project" OR "Circular Impacts Project EU" OR "Circular Pathfinder" OR "Evaluation of CE Development in Cities" OR "Five Category Index Method" OR "Input-Output Balance Sheet" OR "Resource Duration Indicator" OR "Assessing Circular Trade-offs" OR "Circular Benefits Tool" OR "Circular Economy Company Assessment Criteria" OR "Circular Economy Indicators for India" OR "Circular Economy Toolbox US" OR "Closed Loop Calculator" OR "Super-efficiency Data Envelopment Analysis Model" OR "Indicators for Material input for CE in Europe" OR "Indicators for Consumption for CE in Europe" OR "Indicators for Eco-design for CE in Europe" OR "Indicators of Economic Circularity in France" OR "Integrative Evaluation on the Development of CE" OR "Indicators for Production for CE in Europe" OR "Industrial Park Circular Economy Indicator System" OR "Measuring Regional CEeEco-Innovation" OR "Regional Circular Economy Development Index" OR "Recycling Indices for the CE"
Biological cycles	AND	"Biological"
Time span: from January 2010 to August 2020 All publications included (articles, proceedings, reviews, etc.) Every publication stage		

Since the goal of the Research Question 1 is to investigate measurements within CE related to biological cycles, which concerns bio-based materials used, consumed, and cycled in ways that regenerate natural systems (EMF, 2019), the following keywords were entered: "Circular Economy"; each of 55 CE Indicators, identified and classified by Saidani et al. (2019); "Biological". Keywords were inputted in the 31st of August 2020, limiting research to studies written after the 1st of January 2010.

Tab. 3: Material collection process for Question 2

Database search - Web of Science and Scopus (31/08/2020)		
Focus of analysis	Keywords inserted in "Title, abstract or author-specified keywords" for Web of Science and "Article title, Abstract, Keywords" for Scopus	
Environmental impacts	AND	"Environmental impact"
Measurement evaluation	AND	"Methodologies" OR "Assessment" OR "Metrics" OR "Indicators" OR "Tool"
Bioeconomy	AND	"Bioeconomy"
Time span: from January 2010 to August 2020 All publications included (articles, proceedings, reviews, etc.) Every publication stage		

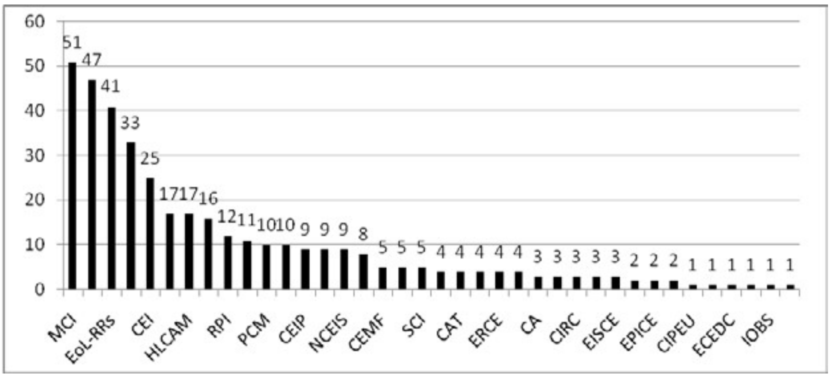
Since the goal of the Research Question 2 is to investigate measurements of environmental impacts within BE, the "Environmental impact" keyword, each of 5 measurement evaluation keywords and the "Bioeconomy" keyword were entered. Keywords were inputted in the 31st of August 2020, limiting research to studies written after the 1st of January 2010.

3. Results and Discussion

3.1. Circular BE measurements

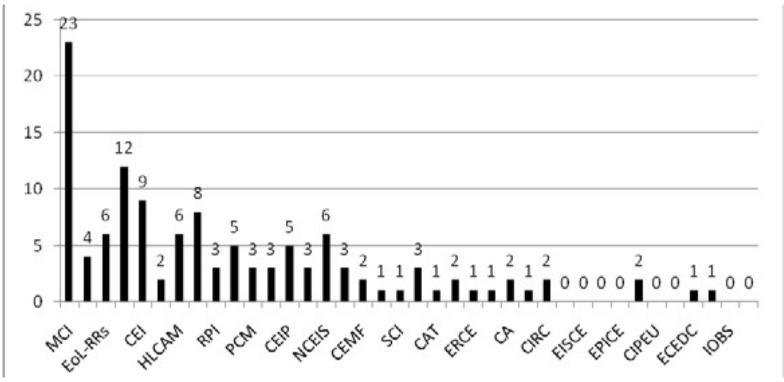
The results of the bibliographic research completed to answer the 1st Research Question are shown in Fig. 1 e Fig. 2.

Fig. 1: Numbers of Circular Economy papers (2010-2020)



Given the "Circular Economy" keyword and each of 55 CE Indicators mentioned in section 2.2, 51 CE papers concerned the Material Circularity Indicator (MCI) by EMF which therefore resulted as the most cited CE Indicator. In the period 2010-2020, 38/55 CE indicators (69%) were published in at least 1 CE paper.

Fig. 2: Numbers of Circular Bioeconomy papers (2010-2020)



Adding the keyword "biological" to the previous scenario, 23 Circular BE papers concerned the MCI which therefore resulted as the most cited Circular BE Indicator in the Circular BE papers of the period 2010-2020. In the same period, 30/55 Circular BE indicators (55%) were published in at least 1 Circular BE paper.

To confirm the results obtained, a further literature insight was completed: EMF, the MCI's developer, collaborates with the International Standard Organization for Standardization/Technical Committee 323 (ISO/TC 323) for standards publication. From an ISO mapping about thousands of standards published in the last years, a strong relationship between CE standards and the ONU Sustainable Development Goals emerged. Therefore, the CE ISO standards and those who collaborate to their publication, strongly contribute to the achievement of the said Goals (Perissinotti Bisoni, 2021). MCI and the principles on which it is based, are part of the principles of the Italian UNI Technical Specification "Misurazioni della Circolaritá – Metodi ed Indicatori per la misurazione dei Processi Circolari nelle Organizzazioni" which is aimed to develop a set of Organizations Circular indicators (Rosso, 2021). MCI is considered as one of the most commonly cited and the most complete micro-level indicators (Lonca et al., 2018; Garza-Reyes et al., 2018; Bracquené et al., 2020). It is widely used as a product and production process measurement tool (Fehrer and Wieland, 2020). The product-level circularity metric can be developed through MCI (Linder et al., 2017; Bracquené et al., 2020; Rufí-Salìs et al., 2021) which is the only micro-level indicator considering product durability (EEA., 2016, Elia et al., 2017, Lonca et al., 2018).

3.2. Environmental impacts measurements within Bioeconomy

The results of the bibliographic research completed to answer the 2nd Research Question are shown in Tab. 4.

Tab. 4: Numbers of Environmental Impact Papers

			n. ENVIRONMENTAL IMPACT PAPERS (2010-2020)				
KEYWORD 1	KEYWORD 2	KEYWORD 3	KEYWORD 1+2	KEYWORD 1+2+3	LCA TOPIC	% LCA	% LCA
environmental impact	methodologies	bioeconomy	3.727	60	50	83	83
environmental impact	assessment	bioeconomy	4.749	73	59	81	
environmental impact	metrics	bioeconomy	1.122	32	27	84	
environmental impact	indicators	bioeconomy	3.121	45	38	84	
environmental impact	tool	bioeconomy	3.436	53	43	81	

Given the base keyword "environmental impact" and each of the 5 measurement evaluation keywords mentioned in section 2.2, a large amount of environmental impact papers were published in the period 2010-2020 (column "Keyword 1+2"). From this articles pool, a subset of Circular BE environmental impact papers was created entering the keyword "bioeconomy" (column "Keyword 1+2+3"): 60 articles were related to the measurement evaluation keyword "methodologies"; 73 to the "assessment" one; 32 to the "metrics" one; 45 to the "indicators" one; 53 to the "tool" one. The 83% on average of this subset concerned the Life Cycle Assessment (LCA) topic. In all keywords combinations, the number of the environmental impact papers increased year by year.

To confirm the results obtained, a further literature insight was completed: LCA is the most compliant environmental assessment tool with CE requirements (Elia et al., 2017; Lonca et al., 2018). The environmental assessment of monitoring of bio-based products and biomass production could be carried out by LCA (Razza et al., 2020). The LCA Life Cycle Inventory could be seen as a common phase of data collection and processing with the MCI Bill of Materials, given their similar specifications (Valencia, 2017; Rufì-Salìs et al., 2021). The LCA methodology is integrable with complementary indicators, such as MCI (EMF, 2019; Rufì-Salìs et al., 2021) since the latter's application concerns life cycle phases (Helander et al., 2019; Rufi-Salis et al., 2021). Lonca et al. (2018) and Niero and Kalbar (2019) indeed considered complementary indicators (calculated using a LCA framework) together with MCI to measure the circularity at micro-level in their analysis of the trade-off between material circularity and environmental efficiency. The highest number of micro-level papers studied in the Harris et al (2020)'s review, used LCA to assess circularity. The LCA methodology could be analyzed in parallel with circularity indicators, including MCI, to conduct combined environmental impacts and circular assessments (de Oliveira et al., 2021).

4. Conclusions

Circular Economy and Bioeconomy, intended as of the CE developing area, seem to be two of the most current topics of the last years thanks to the several policies and directives that were established both at European level and globally. The consequences of this scenario come to fruition through several funding plans pushing the production system to look at CE and BE models to reduce its environmental impact.

This study aimed to increase the understanding of the measurement tools related to the Circular BE and environmental impacts. The research showed that MCI is the most cited CE and Circular BE Indicator. The environmental impact measurement tool that showed to be the most popular is the LCA. Furthermore, the literature insight performed confirmed both MCI and LCA as effective measurement tools.

Therefore, the scenario revealed of intense scientific activity suggests a potential need for further investigation in these tools. A possible future research opportunity could be represented by the comprehension whether the mentioned tools could be applied on an integrated approach, filling the knowledge gap about the coexistence of circularity and environmental sustainability.

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Result updates

The results of the quali-quantitative assessment refer to the period 01/01/2010-31/08/2020. To provide up-to-date results, the circular and environmental indicators detected in the study have been re-evaluated according to the period 01/09/2020-31/12/2022 to check for their trend consistency.

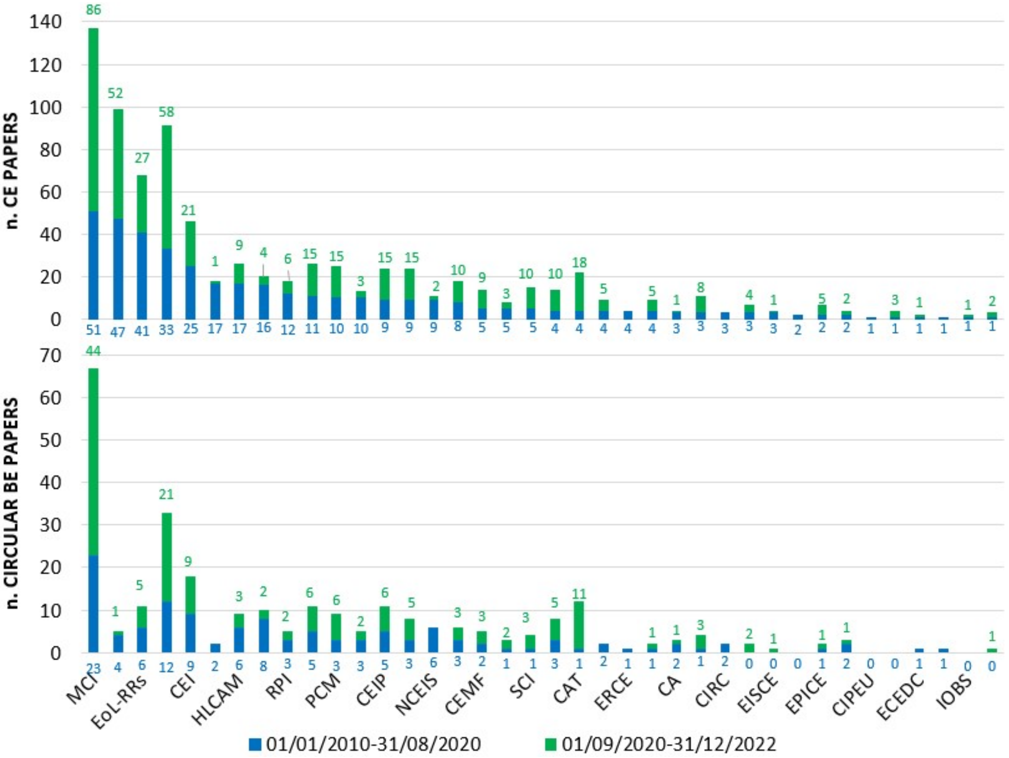

Figure 3.1: Numbers of CE and circular BE papers (2010-2022)

The MCI confirmed its leadership as the most present product circularity assessment tool in both CE and circular BE articles (with 86 and 44 citations, respectively) published in the period September 2020-December 2022. 169% and 191% are the percentage increases of the MCI-centric articles detected in the CE and circular BE papers, respectively, when compared to those of the period January 2010-August 2020.

			n. BIOECONOMY ENVIRONMENTAL IMPACT PAPERS									
KEYWORD 1	KEYWORD 2	KEYWORD 3	KEYWORD 1+2		KEYWORD 1+2+3		LCA TOPIC		% LCA		$\overline{\%\ LCA}$	
			2010-2020	2020-2022	2010-2020	2020-2022	2010-2020	2020-2022	2010-2020	2020-2022	2010-2020	2020-2022
environmental impact	methodologies	bioeconomy	3.727	1.738	60	97	50	82	83	85	83	85
	assessment		4.749	1.839	73	108	59	92	81	85		
	metrics		1.122	504	32	39	27	34	84	87		
	indicators		3.121	1.232	45	78	38	67	84	86		
	tool		3.436	1.300	53	74	43	62	81	84		

Figure 3.2: Numbers of bioeconomy environmental impact papers (2010-2022)

Concerning the environmental impact assessment tool, the LCA was still the most cited methodology in the period September 2020-December 2022 (85% average of the bioeconomy environmental impact papers) with an average increase of 2 percentage points compared to the period January 2010-August 2020.

3.2 Analysis of the literature integration/combination models between circularity and environmental assessments

3.2.1 Integration of Circular Economy metrics with Environmental Impact Assessment: methodological proposal

This section analyzes the literature integration/combination patterns between circularity and environmental assessments, and a MCI-LCA methodological proposal is outlined.

2. Gallo, F., Manzardo, A., Camana, D., Scipioni A. (2022) Integration of Circular Economy metrics with Environmental Impact Assessment: methodological proposal. Italian LCA Network 16th Annual Meeting - Abstract Book. ISBN: 9791221004588.

Results summary

Two integration/combination models are identified in the article: the separate conduction in which there are neither methodology nor results integrations, and the single tool separate conduction in which the environmental and circular assessments are conducted separately while the independent results are combined each other and joint in a single tool.
Both models lead to a non-univocal consensus and to evaluations not yet consolidated which suggests a potential need for further investigation in alternative models. One of the latter is outlined thanks to several literature insights which suggest the possibility for MCI to provide extra information within a more extensive LCA evaluation in a framework where either the methodologies or the results are integrated.

Integration of Circular Economy metrics with Environmental Impact Assessment: methodological proposal

Federico Gallo[1], Alessandro Manzardo[1], Daniela Camana[1], Antonio Scipioni[1]

Abstract: Based on literature evidences confirming Material Circularity Indicator (MCI) and Life Cycle Assessment (LCA) as reliable metrics by which measure Circular Bioeconomy and environmental impacts, respectively, and defining the current integration/combination models between circularity and environmental assessments, a specific MCI-LCA methodological model was proposed. The model's consolidated LCA framework might represent a simplification feature, making the results easier to interpretate and explain. In order to assess its applicability and effectiveness and, therefore, fill the knowledge gap about the coexistence of circularity and environmental sustainability, appropriate case studies may be selected for further investigation.

1. Introduction

Circular Economy (CE) and Bioeconomy (BE), which is one of the CE development fields, appear to be two of the most topical debated themes in recent years, due to a slew of regulations and directives enacted both at the European and worldwide levels. The effects of this scenario are expressed through a number of financial initiatives that encourage the manufacturing system to adopt CE and BE models in order to reduce its environmental impact.

Gallo et el. (2021) showed that the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation (EMF) was the most cited CE and Circular BE Indicator, whereas the environmental impact measurement tool that showed to be the most popular was the Life Cycle Assessment (LCA). These results, as well as the literature analysis performed, confirmed both MCI and LCA as effective measurement tools.

The goal of this research is to comprehend whether the mentioned tools could be applied on an integrated approach, filling the knowledge gap about the coexistence of circularity and environmental sustainability.

2. Research question and methodology

The purpose of this study is to implement an integrated model between MCI and LCA methodologies.

Firstly, an overview on metrics methodologies is reported.

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Secondly, a literature analysis on recent circularity and environmental assessment models is performed outlining the integration/combination patterns.

Thirdly, based on literature findings the MCI-LCA methodological proposal is implemented.

Conclusions and future steps are finally suggested.

3. Metric methodologies

3.1. Material Circularity Indicator methodology

The MCI is a tool developed by the EMF to quantify the circularity of a product's component material flows. The MCI takes a holistic approach to the product's whole life cycle, from the quantity of virgin raw material used to the amount of waste produced at the end of the use phase, while also considering the product's lifespan in comparison to the industry average. MCI has a range of values from 0 to 1, with 0 representing a totally linear product and 1 representing a completely circular product.

According to EMF (2019), both technical and biological materials can be considered circular if the following principles are respected:

1. Respecting regeneration capacity of the material by the exploited source
2. Using feedstock from reused or recycled sources
3. Keeping products in use longer (e.g., by reuse/redistribution/increase durability)
4. Reusing components or recycling materials after the use of the product
5. Making more intensive use of products (e.g. via service, sharing or performance models)
6. Returning to the environment of nutrients in bio-available form.

The MCI is an index based on four indicators (Tab. 1) that analyze product circularity in an accurate and direct manner.

Tab. 1: MCI indicators

INDICATOR	DESCRIPTION
Virgin feedstock	Calculated from the percentage of material from recycling, reuse and raw material from biological cycle (from sustainable sources) present in a product
Non-recoverable waste	Calculated from the percentage of waste that is reused, recycled, biological waste that is composted, biological waste that is incinerated with energy recovery. Non-recoverable waste is sent for disposal in landfills or incineration (with or without energy recovery)
Linear Flow Index	Percentage of material that has a linear trend in the process (incoming virgin material, outbound non-recyclable waste)
Utility Index	Product lifespan both from a point of view of time and intensity of use

MCI is flanked and integrated by optional indicators that offer a management analysis of the product both from an impact (understanding on which materials, parts or products to focus) and risk (understanding what are the potential risks in relation to management priorities) point of view.

The MCI determination is primarily performed by the Bill of Materials (BoM) concerning a list of the parts or components (and the type and amount of material they are made of) that are required to build a product.

Secondly, the MCI calculation concerns formulas applicable to product-level technical and biological cycles. Each of the following indicators must be quantified for each technical and biological component that enters the various finished products. The circularity of the product is deduced from the aggregation on a mass basis (weighted average) of each individual component of the technical and biological cycle. The first step consists in the calculation of V as the fraction of the mass M of the material/product/component that originates from virgin material, i.e. material extracted and processed directly from nature:

$V=M(1-F_R-F_U-F_S)$ eq.1

where F_R is the fraction that derives from recycled material, F_U is the fraction that derives from reused material (i.e. from production waste reused as raw materials or semi-finished products as inputs to the production process), and F_S is the fraction of a product's biological feedstock from Sustained Production which respects the regeneration capacity of the product within natural systems.

This indicator then helps to determine whether the input material/product/component is the result of a linear or circular process. Concerning the recycled fraction, the methodology enhances reuse, repair, recycling, and maintenance operations. Reuse refers instead to those materials that are reintroduced into the cycle with the same characteristics, functionality and shapes as the original product.

The second step involves the calculation of W_0 as the mass M of the material/product/component that, once used, is destined to be treated directly in landfill or sent for energy enhancement:

$W_0=M(1-C_R-C_U-C_C-C_E)$ eq.2

where C_R is the fraction sent for recycling, C_U is the fraction reused, C_C is the fraction comprising uncontaminated biological materials that are being composted, and C_E comprising biological materials from Sustained Production being used for Energy Recovery.

The third step involves the calculation of W_C as the fraction of the mass M of the material/product/component that is destined for treatment in landfills following recycling operations:

$W_C=M(1-E_C)C_R$ eq.3

where E_C represents the efficiency of recycling processes.

The linear mass W_F calculation of the material/product/component concerns the fraction of the mass M deriving from the preparation operations of the secondary raw materials following the recycling processes:

$W_F=M\,((1-E_F)F_R)/E_F$ eq.4

where F_R is the fraction resulting from recycling processes, while E_F corresponds to the preparation process efficiency of secondary raw materials.

The total linear W mass is determined as follows:

$W=W_0+(W_F+W_C)/2$ eq.5

The Linear Flow Index (LFI) of the material/product/component under consideration is then defined:

$LFI= (V+W)/(2M+ (W_F-W_C)/2)$ eq.6

LFI has a value between 0 and 1, where 1 means that the material/product/component is completely linear.

The method introduces an utility function F(X) for enhancing two aspects: 1) the opportunity of keeping the product in the use phase as long as possible, and therefore having a longer useful life (L) thanks for example to direct reuse or the possibility of being repaired; 2) the fact of having improved performance (e.g. in the case of a packaging with better preservation characteristics of the content). The product usefulness is therefore linked to two factors: the relationship between the good lifespan L and the lifespan of market average goods L_{AVG}, and the relationship between the good intensity of use U and the intensity of use of market average goods U_{AVG}.

$X=L/L_{AVG}*U/U_{AVG}$ eq.7

The F(X) Utility function is defined as follows:

$F(X)=0,9/X$ eq.8

The value 0.9 is a conventional value established in order to differentiate materials/products/components with a linearity equal to 1 but with improved performance compared to the market average product.

The final product circularity is possible by the following equation:

$MCI=1-LFI*F(X)$ eq.9

3.2. Life Cycle Assessment methodology

In the increasingly affirmed concept of "sustainable development" for which the spheres of economic, social and environmental development must be integrated together, the innovative philosophy of thought called "Life Cycle Thinking" (LCT) is born. The new idea compared to the past is to consider a product as a set of operations, input and output flows of materials and forms of energy associated with all the steps of its life cycle, from design to disposal and recovery or final disposal. It is from this new concept that the LCA methodology is developed as the main operational tool, in particular in the environmental field, which allows a complete study of the product considering all the processes connected with its entire life cycle.

The LCA methodology is an objective process of evaluation of energy and environmental loads related to a process or activity, carried out through the identification of energy and materials used and waste released into the environment. The assessment includes the entire life cycle of the process or activity, including the extraction and processing of raw materials, manufacture, transport, distribution, reuse, recycling and final disposal.

In order to have a greater uniformity of the evaluations and, consequently, more homogeneous and comparable results on the same products, the UNI EN ISO 14040-44 standards was born, which describes how to carry out a complete LCA study for any type of product; these are not product-specific rules, but contain general requirements applicable to all products, regardless of their nature.

In particular, an LCA study consists of the following phases:

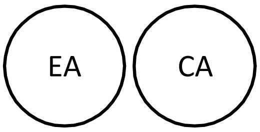
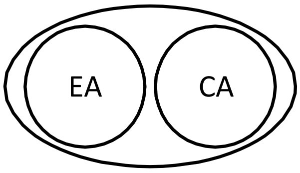
1. goal and scope definition (UNI EN ISO 14044 - §4.2): ;
2. life cycle inventory analysis (UNI EN ISO 14044 - §4.3);
3. life cycle impact assessment (UNI EN ISO 14044 - §4.4);
4. life cycle interpretation (UNI EN ISO 14044 - §4.5).

4. Results

4.1. Integration/combination models

In recent years there has been an increasing theorization about the possibility of integration/combination between environmental assessment (EA) and circularity assessment (CA). Stated that integration is defined as the process of making more elements a whole, the integration/combination models of the studies identified by Rigamonti and Mancini (2021) may be summarized as follows:

Tab. 2: Literature integration/combination models

MODEL	METHODOLOGY INTEGRATION	RESULTS INTEGRATION
SEPARATE CONDUCTION  	NO: EA and CA are conducted separately	NO: independent results are combined each other
SINGLE TOOL SEPARATE CONDUCTION  	NO: EA and CA are conducted separately	YES: independent results are combined each other and joint in a single tool

Bracquené et al., 2020, Glocic et al., 2020, Lonca et al., 2018, Schmidt et al., 2020, and Stanchev et al., 2020 applied the separate conduction model, whereas Mantalovas and Di Mino (2020) and Niero and Kalbar (2019) focused on single tool separate conductions. Apart from understanding that circularity indicators do not seem to be suitable to be used alone (Rigamonti and Mancini, 2021), both models lead to a non-univocal consensus and to evaluations not yet consolidated which suggests a potential need for further investigation in alternative models.

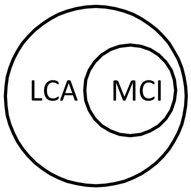
4.2. Material Circularity Indicator-Life Cycle Assessment methodological proposal

The specific context of this study aims to hypothesize an integration model between LCA and MCI as tools for assessing environmental impact and circularity, respectively.

Rigamonti and Mancini (2021)'s research concerning the integration/combination of LCA with circularity indicators emerged that 5 out of 8 recent studies applied MCI as circularity assessment tool. MCI can be complemented by optional impact indicators that could be determined by an LCA approach (EMF, 2019; Rigamonti and Mancini, 2021) since MCI can be determined along all stages of the product life cycle (Helander et al., 2019; Rufì-Salìs et al., 2021). Furthermore, to perform integrated environmental and circular evaluations, the LCA approach might be studied with circularity indicators, such as MCI (de Oliveira et al., 2021), provided that an integrated methodology composed of both tools should be set to the same system boundaries (Mantalovas and Di Mino, 2020). Given their comparable standards, the LCA Life Cycle Inventory and the MCI Bill of Materials might be considered a shared step of data gathering and processing (Valencia, 2017; Rufì-Salìs et al., 2021; Gallo et al., 2021).

The research evidences suggest the possibility for MCI to provide extra information within a more extensive LCA evaluation. Therefore, the study's methodological proposal seeks to implement the MCI methodology as part of the LCA one. In order to achieve this goal, the following integration model was implemented:

Tab. 3: Proposed integration model

MODEL	METHODOLOGY INTEGRATION	RESULTS INTEGRATION
MCI SUBSET OF LCA  	YES: MCI is integrated within LCA	YES: MCI output is integrated within the LCA framework

In a more applicative framework the above model could be represented as follows:

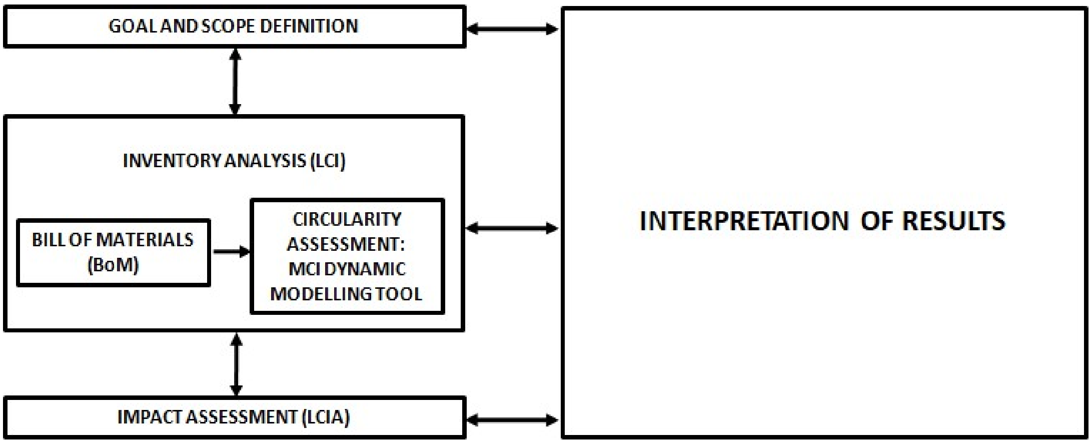


Fig. 1: MCI-LCA methodological proposal

5. Conclusions

This study aimed to comprehend whether the MCI and LCA, as Circular Bioeconomy and environmental impacts assessment tools respectively, could be applied on an integrated approach, filling the knowledge gap about the coexistence of circularity and environmental sustainability. Based on the current literature integration/combination models, a specific MCI-LCA methodological model was proposed. Stated the complexity of performing integrated analysis, the model's consolidated LCA framework might represent a simplification feature, making the results easier to interpretate and explain.

The next research step could be the detection of different case studies whose outcomes may be analyzed and contextualized within the model proposed in order to assess its applicability and effectiveness. As a consequence, appropriate conclusions may be drawn possibly suggesting ideas for improvement with the final goal to translate the results obtained into operational indications so that bodies responsible (e.g. ISO Technical Committee 323 of which EMF is a contributor) may be helped to implement CE strategies.

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3.3 Development and application of the MCI-LCA integrated method

3.3.1 Integration of a circular economy metric with Life Cycle Assessment: methodological proposal of compared agri-food products

This section addresses the methodological developments needed to apply MCI-LCA integrated method to agri-food products by using complementary indicators (calculated using the LCA methodology) together with the MCI through a Cartesian graph to obtain an in-depth analysis of the circular and environmental performance of the products. It contains the following publication:

3. Gallo, F., Manzardo, A., Camana, D., Fedele A., Scipioni A. (2023) Integration of a circular economy metric with Life Cycle Assessment: methodological proposal of compared agri-food products. The International Journal of Life Cycle Assessment. doi: 10.1007/s11367-022-02130-0.

Results summary

In the methods part of the publication, the Ellen MacArthur Foundation suggestion to use complementary indicators (calculated using the LCA methodology) together with the MCI is received to obtain an in-depth analysis of the circular and environmental performance of the products. As a result, a MCI-LCA methodological integration model is proposed in which compared case studies are selected in the agri-food sector since their products encompass both biological and technical materials.

In the results section, an innovative circular and environmental assessment panel of coupled products belonging to the same product category is implemented. Specifically, five scenarios are detected in which the relationship between circularity and the relative environmental impacts varies according to the trend line slope linking the product analyzed to another comparable product.

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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Integration of a circular economy metric with life cycle assessment: methodological proposal of compared agri-food products

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Abstract

Purpose Based on the Material Circularity Indicator (MCI) and Life Cycle Assessment (LCA) as effective circular and environmental measurement tools, respectively, the purpose of this article is firstly to propose an approach in which to apply the mentioned tools to correlate circularity with environmental impacts. Secondly, it is to test and analyze the model through compared case studies and assess its applicability as an effective product circularity-environmental assessment tool.

Methods To propose a methodology that correlates circularity and environmental impacts, the methodologies underlying MCI and LCA were considered the most recognized in the literature. The Ellen MacArthur Foundation suggestion to use complementary indicators (calculated using the LCA methodology) together with the MCI was received to obtain an in-depth analysis of the circular and environmental performance of the products. As a result, an integrated MCI-LCA methodological integration model was proposed in which compared case studies were selected in the agri-food sector since their products encompass both biological and technical materials.

Results and discussion From the examination of the graphical representation patterns of the interpretation of results phase, five scenarios for the circular-environmental assessment of compared products were detected depending on the characteristics of the trend line: scenarios no. 1 and 2 where circularity led to higher environmental impacts, scenario no. 3 where circularity did not affect environmental impacts, and scenarios no. 4 and 5 where circularity led to lower environmental impacts. Compared to studies in the current literature, the added value of the application of the proposed model was to allow a comprehensive and holistic assessment through an innovative circular and environmental assessment panel of coupled products belonging to the same product category.

Conclusions What the authors expected from the principles of the proposed model and the results achieved make the model applicable. Environmental Product Declarations of coupled products were used as an information source for both circular and environmental evaluations. Circularity did not always lead to a reduction of environmental impact, as it depended on the type of impact category and product. More compared case studies are required to be applied to the proposed integrated model to strengthen the assumption made in the study, determine eventual adjustments in the weighing system of the MCI methodology, and for the detected circular-environmental scenarios to try to bridge the gap of standardized regulations on circularity measurement framework, which have led to the current nonuniform indicator approaches.

Keywords Circular economy · Material Circularity Indicator · MCI · Life Cycle Assessment · LCA · Environmental sustainability · Environmental Product Declaration · EPD

Abstracts

ADP-E	Abiotic Depletion Potential-Elements
ADP-FF	Abiotic Depletion Potential-Fossil Fuels
AP	Acidification Potential
BE	BioEconomy
BoM	Bill of Materials
C	Core processes
CA	Circular Assessment
CE	Circular Economy
D	Downstream processes
EA	Environment Assessment
EMF	Ellen MacArthur Foundation
EP	Eutrophication Potential

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EPD	Environmental Product Declaration
EU	European Union
F(X)	Utility Function
GPI	General Programme Instructions
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFI	Linear Flow Index
M	Product material flow
MCI	Material Circularity Indicator
NON-ORG	Product non-organic version
ORG	Product organic version
PCR	Product Category Rules
POFP	Photochemical Oxidation Formation Potential
S	Trend line slope
U	Upstream processes
V	Product virgin raw material
W	Product unrecoverable waste
WSF	Water Scarcity Footprint

1 Introduction

Resource scarcity and the problem of waste management are two of the key issues in contemporary society that encourage reflection on the benefits of transitioning to a circular economy (CE) model. CE is defined by the Ellen MacArthur Foundation (EMF 2019) as a global economic model that decouples economic growth and development from the consumption of finite resources. In a "cyclical" system, the waste concept does not exist, and waste is referred to as potential materials to be transformed into new resources. With resource extraction and transformation leading to half of total greenhouse gas emissions and more than 90% of biodiversity loss and water stress, the European Green Deal has launched a concerted strategy for a climate-neutral, resource-efficient, and competitive economy (European Union 2022a). According to the 2020 CE Action Plan of the European Commission, extending the CE from precursors to traditional economic operators will contribute significantly to achieving climate neutrality by 2050 and disassociating economic growth from the use of resources, while ensuring the long-term competitiveness of the EU (EU 2022c). The mentioned decoupling is one of the strategies of the Sustainable Consumption and Production policies of the UN (United Nations Environment Programme 2022) which push the production system to look at CE models to reduce its environmental impact.

Bioeconomy (BE), the socioeconomic system that encompasses and interconnects economic activities that use renewable bioresources from the soil and sea (also called biobased resources) to produce food, materials, and energy (EU 2022a), represents a fundamental variation of CE as one of its developing areas. In addition to relying on renewable resources, BE feeds the "biological cycle" that is intended to be the recovery and enhancement of energy of organic waste derived from waste production processes (MATTM and MISE 2017). The 2018 EU Bioeconomy Strategy aims to reduce environmental impact with a three-tier action plan that includes strengthening and scaling biobased sectors, unlocking investments and markets, deploying local bioeconomies rapidly throughout Europe, and understanding the ecological boundaries of the bioeconomy (EU 2022b). The consequences of this strategy come to fruition through funding plans. One of these includes 95.5 billion € under Horizon Europe for thematic groups including "Food, Bioeconomy, Natural Resources, Agriculture & Environment" for the period 2021–2027 (EUcalls 2021).

In this framework, BE as a means of reducing environmental impact was found to be central to international policies. Many CE indicators have been developed by different stakeholders with different scopes and applications (Saidani et al. 2019) to measure and assess the achievement of specific CE targets (Morseletto 2020). However, there is no prevailing opinion on their implementation feasibility (de Oliveira et al. 2021) that should aim to improve the environmental performance of society (Harris et al. 2021). de Oliveira et al. (2021) underline the need to integrate CE indicators with methodologies that support environmental sustainability. The CE monitoring process through specific measurement tools (i.e., with respect to material consumption and environmental impacts) is an open field of research whose importance is also outlined in the European CE Action Plan (EUR-LEX 2020). The Material Circularity Indicator (MCI) is one of the most cited CE and BE indicators in recent years. MCI was developed by the EMF, focuses its analysis on material flows occurring in relation to a product, and is among the most recognized product-level circular assessment tools by European Environment Agency (2016) and Rigamonti and Mancini (2021). The highest number of articles studied in the reviews by Harris et al. (2021) used LCA to assess circularity. Gallo et al. (2021) showed that 83% on average of circular BE papers published in the period 2010–2020 related to the LCA topic for the environmental impact evaluation. LCA is one of the most compliant environmental assessment tools with CE requirements (Corona et al. 2019; Sassanelli et al. 2019), also for biological materials (Razza et al. 2020). It is also generally accepted that LCA should be the CE assessment tool to ensure a positive balance of efforts and benefits in both new product design and increased recycling (Haupt and Zschokke 2017). An important result of the study by Parchomenko et al. (2019) is the flexibility of the LCA approach to be combined with a variety of CE metrics due to the wide range of applications. Peña et al. (2021) stated that environmental metrics, such as those of LCA, are compliant with CE assessment. The research by Rigamonti and Mancini (2021) showed that all studies applied LCA as an environmental assessment tool.

In recent years, there has been increasing theorization about the possibility of integration/combination between environmental assessment (EA) and circularity assessment (CA). Declaring that integration is defined as the process of making more elements a whole, the current integration/combination models of the studies may be summarized into two models. Some authors applied the separate conduction model in which EA and CA are conducted separately, and independent results are combined with each other. The applications of such model were on washing machines (Bracquené et al. 2020), alkaline batteries (Glocic et al. 2020), tires (Lonca et al. 2018), food packaging (Pauer et al. 2019), PET bottles (Schmidt et al. 2020), anaerobic treatments of dairy processing effluents (Stanchev et al. 2020), and poultry production (Rocchi et al. 2021). Other authors focused on integrated conductions in which EA and CA are conducted separately, and independent results are combined together and joint in a single tool: Mantalovas and Di Mino (2020) focused on asphalt mixtures, Niero and Kalbar (2019) on beer packaging, and Rufí-Salìs (2021) on urban agriculture. Apart from understanding that circularity indicators do not seem to be suitable to be used alone (Rigamonti and Mancini 2021), both models lead to a non-univocal consensus and to evaluations not yet consolidated, which suggests a potential need for further investigation in alternative models. Attempting to investigate the latter, MCI finds its methodological complement in life cycle management tools, specifically the LCA, as recalled by Rufí-Salìs et al. (2021). The LCA methodology is integrable with complementary indicators, such as MCI (Ellen MacArthur Foundation 2019; Rufí-Salìs et al. 2021) since the application of the latter concerns the phases of the life cycle (Helander et al. 2019). To perform integrated environmental and circular evaluations, the LCA approach could be studied with circularity indicators (de Oliveira et al. 2021; Rigamonti and Mancini 2021), provided that an integrated methodology composed of both tools should be set to the same system boundaries (Mantalovas and Di Mino 2020). Regarding the data collection phase, the MCI Bill of Materials could represent a means to perform the LCA Life Cycle Inventory (Rebitzer et al. 2004; Valencia 2017).

So far, few agri-food studies have included both MCI and LCA application: Rocchi et al. (2021) focused on poultry production performing environmental and circular (with a modified MCI adapted to biological materials) assessments separately to achieve combined conclusions; Niero and Kalbar (2019) assessed the performance of beer packaging through a separate application of MCI and LCA whose results were combined in a single tool; Rufí-Salìs et al. (2021) applied an urban agriculture assessment in which MCI and LCA methodologies were integrated together in an innovative set of indicators represented in specific graphs.

Literature studies have shown that there are no case studies applied to current integration models to assess whether circularity (both in terms of biological and technical cycles according to the EMF methodology (2019)) means reducing environmental impacts. Haupt and Zschokke (2017) already stated that the most circular solution is not necessarily the most environmentally preferable option. Therefore, based on MCI and LCA as effective circular and environmental measurement tools, respectively, the purpose of this article is firstly to propose an approach in which to apply the mentioned tools to correlate circularity with environmental impacts. Secondly, it is to test and analyze the model through compared case studies and assess its applicability as an effective product circularity-environmental assessment tool which indicates whether applying circular principles can improve or worsen the environmental impacts of products.

This article is structured into the following sections:

Methods (Sect. 2): The MCI-LCA methodological integration model is explained in Sect. 2.1, and the description of case studies is reported in Sect. 2.2.

Results (Sect. 3): In this section, results are reported for each case study detected according to the objective and scope definition phase (Sect. 3.1), the life cycle inventory phase (Sect. 3.2) with relative inventory indicators from EPD (Sect. 3.2.1), the circularity assessment (Sect. 3.3), the Life Cycle Impact Assessment phase (Sect. 3.4), and the interpretation of results phase (3.5).

Discussion (Sect. 4): Discourses and limitations regarding specific sections of the article are discussed in this sector.

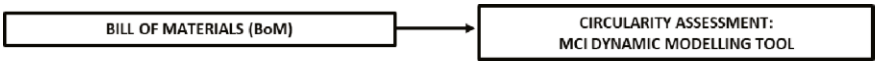
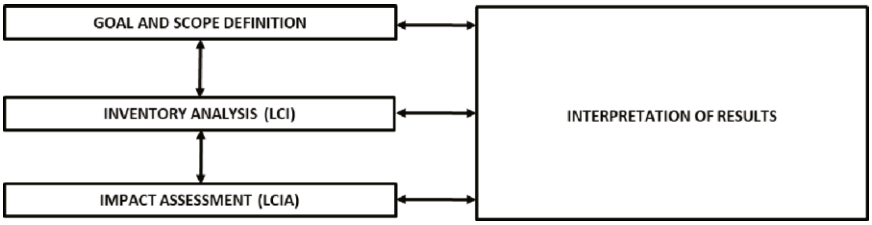
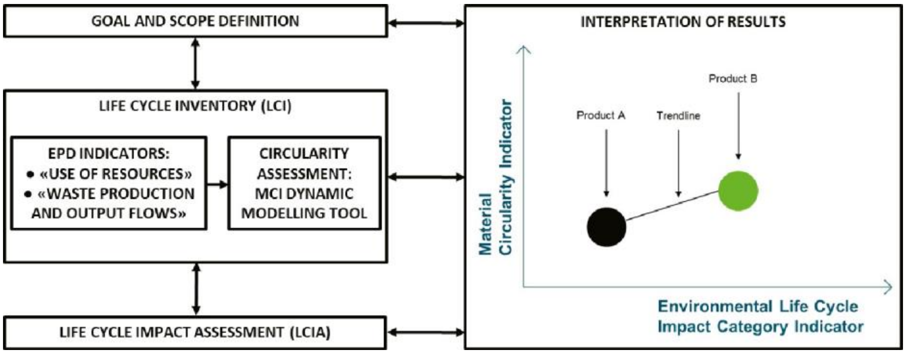
Conclusions (Sect. 5): Main outcomes of the research are reported, and the next steps are finally suggested.

2 Methods

2.1 MCI-LCA methodological integration model

To propose a methodology that correlates circularity and environmental impacts, the methodologies underlying MCI and LCA (Table 1) were considered the most recognized in the literature. The EMF suggestion to use complementary indicators (calculated using the LCA methodology) together with the MCI was received to obtain an in-depth analysis of the circular and environmental performance of the products. The matching and comparison of these two metrics was possible through a Cartesian graph (suggested by the same EMF methodology (2019)) where MCI is on the Y-axis and the environmental life cycle impact category indicator on the X-axis (Table 1). The determination of environmental indicators takes place

Table 1 Block diagrams of assessment tools: MCI (a), LCA (b), and integrated MCI-LCA (c)

No.	ASSESSMENT TOOL	BLOCK DIAGRAM
a	MCI (EMF, 2019)	
b	LCA (ISO 14040-14044, 2006)	
c	MCI-LCA (Adapted from EMF (2019) and ISO 14040-14044 (2006))	

according to the phases of goal and scope definition, inventory analysis, and impact assessment of the ISO 14040–14044 methodology, while the MCI is calculated through the reviewed Dynamic Modelling Tool (2015) starting from some of Environmental Product Declarations (EPD) indicators. EPD was exploited as a widely recognized data source according to the international standard ISO 14025 (2010).

The MCI-LCA integrated model is composed of the following phases:

- Goal and Scope Definition (ISO 14040–14044 2006b) whose goal aims to define the application, the reasons for applying the model to the product, the intended audience to whom to communicate the results, and whether the latter are intended to be used in comparative assertions intended to be disclosed to the public. The scope phase aims to identify the methodology used (i.e., the life cycle impact assessment methodology and reference documents and tools through which the MCI-LCA assessment is performed), the declared unit (understood as a product measure respect of which the environmental impacts are quantified), the system boundaries and relative assumptions and cut-off criteria depending on the considered life cycle processes, and the allocation procedure where the environmental load associated with each process is divided among the various outputs.
- Life Cycle Inventory (LCI) Analysis (ISO 14040–14044 2006b) aims to build an analogical model of reality to represent as faithfully as possible all energy and matter exchanges among process units of a product system. This is possible through data collection with reference to the research goal. An inventory analysis is carried out iteratively. New data requirements or constraints may be discovered when more information is gathered about the system, necessitating a modification in the data collection methods to continue achieving the goal of the study.

  According to ISO 14025 (2010) and General Programme Instructions (EPD International AB 2019) applicable to this study (which provide the basis of the overall EPD administration and operation), data deriving from this phase are categorized in the following EPD indicators:

  - The indicators for use of resources as renewable and non-renewable primary energy—used as raw materials and secondary raw materials.
  - The indicators for waste production and output flows as hazardous and nonhazardous waste disposed, radioactive waste disposed, components for reuse, material for recycling, and materials for energy recovery.

    As a result of the LCI phase, these indicators represent net flows of resources, waste, and output crossing the system boundaries (EPD International

AB 2022). Being the Bill of Materials (BoM), a list of the parts or components (and the type and amount of material they are made of) that are required to build a product (EMF 2019), it may be seen as a means through which to perform the LCI. Therefore, since the above EPD indicators are based on the LCI phase, they incorporate the BoM itself and can be the input for the next circularity assessment phase.

- Circularity assessment (EMF 2019) concerns the MCI calculation and is related to formulas that apply to technical and biological circular cycles at the product level: biological cycles, in which materials and products are returned to the bioeconomy in the process of natural systems regeneration, and technical cycles, in which products, components, and materials are kept in the market at the highest possible quality and for as long as possible through repair and maintenance, reuse, refurbishment, remanufacture, and ultimately recycling. The product circularity (MCI = 1 represents 100% circularity of the product) is the result of mass-related aggregation (weighted average) of each individual component of the technical and biological cycle. According to the EMF (2019), the MCI is essentially constructed from a combination of three components (Eq. 1 in the case where the mass of unrecoverable waste generated in the process of recycling parts of a product is equal to the mass of unrecoverable waste generated when producing recycled feedstock for a product): the Linear Flow Index (LFI) as the percentage of material flow M originating from virgin raw material V and ending up as unrecoverable waste W attributed to the product, and the utility function F(X) of the linear component of material flows represented by the product of the length and intensity of the use phase of the product.

$$LFI = (V + W)/2M \tag{1}$$

The interpretation of Eq. 2 is the subtraction of "LFI * F(X)" as the linear flow of the product from "1" as the maximum circular flow of the same product to determine its circularity level.

$$MCI = 1 - LFI * F(X) \tag{2}$$

In this study, F(X) is considered to be negligible. The reason for this is that the use phase in all the case studies considered is out of the system boundaries.

There are two kinds of input for the MCI calculation: the feedstock flows (about virgin, recycled, reused, and biological mass streams used to produce a product) and the destination after use flows (about product streams to landfill, recycling, reuse, energy recovery, and composting).

Based on the use of resource indicators from the LCI phase, the feedstock flow modeling concerns the mass conversion of energy streams (renewable and non-renewable primary energy—used as raw materials) from MJ to kg through their lower calorific value (MJ/kg) to make them comparable with primary and secondary raw materials mass flows. According to CEN/TR 16,970 (2016), primary energy resources used as raw materials are quantified by multiplying the mass of the resources by their lower calorific value, and therefore the above-mentioned mass conversion is carried out by reverse operation.

A deeper understanding is necessary to explain the relationship between biological feedstock and primary raw materials. According to EMF (2019), the biological feedstock concerns the fraction of a product from Sustained Production: it refers to the extraction of natural materials at volumes and employing practices which aim to maximize the regeneration of natural systems (intended as avoiding the use of non-renewable resources and preserving/enhancing renewable ones) in the indigenous ecosystems (to reduce the risk of increasing the number of invasive species) by for example supporting the development of healthy soils. In this research, the biological feedstock is assumed to be present in the primary biological raw materials of organic products. The latter's principles (EUR-LEX 2018), in fact, seem to be complementary with those of EMF since they concern an overall system of farm management and food production that includes best environmental and climate action practices, a high level of biodiversity, and the preservation of natural resources (e.g., by the maintenance and enhancement of soil life and natural soil fertility, soil stability and soil biodiversity, and the limitation of the use of non-renewable resources).

Indicators on waste production and output flows selected from the LCI phase are used for the destination after use modeling. In particular, composting flows are assumed to be at 11% of all destination after use flows as the percentage of municipal food waste in the EU composted in 2020 (Eurostat 2022; European Environment Agency 2020). The efficiency of the recycling process used for the portion of a product collected for recycling is assumed to be 49% for all case studies, as the municipal waste recycling rate for 2020 in the EU (EEA 2022).

- Life cycle impact assessment (LCIA) (ISO 14040-14044 2006a) aims to evaluate the significance of potential environmental impacts using the LCI results. According to the GPI (EPD International AB 2019), the environmental LCIA indicators are the acidification potential (AP), the eutrophication potential (EP), the global warming potential (GWP), the photochemical oxidant creation potential (POFP), the abiotic depletion potential-elements (ADP-E), the abiotic depletion potential-fossil fuels (ADP-FF), and the water scarcity footprint (WSF). According to EU (2010), environmental impact categories are taken directly from the CML-IA baseline method (EP, GWP, ADP-E, ADP-FF) and the CML-IA non-baseline method (AP), and the WSP water scarcity category is based on the AWARE method (WULCA 2022). The indicator scores are normalized to maximum internal values: for each impact category, the maximum value is selected as a standard reference against which a normalization is performed. Normalization represents a linear scale conversion that assigns the same absolute values to the same relative variations (Sola and Sevilla 1997). Specifically, it aims to scale the data to the specific range between 0 and 1 so that they can be manageable for the interpretation phase of the results (Sect. 3.5).

Information for the following life cycle interpretation phase is also provided by the LCIA phase. If the impact assessment shows that the scope of the research cannot be reached, it may be necessary to adjust the purpose and scope of the study. Impact assessment can also involve an iterative process to review the objective and scope of the LCA study.

- The interpretation of results is the phase where the results of the circularity assessment and the life cycle impact category analysis are combined. The results of the interpretation phase should reach conclusions, clarify constraints, and offer recommendations while remaining compatible with the purpose and scope established. This phase includes integrated circular-environmental conclusions which are based on a relative approach and suggest probable implications. The iterative process of assessing and modifying the scope, as well as the nature and quality of the data obtained in a way that is compatible with the established goal, may be part of the interpretation phase (ISO 14040-14044 2006b).

Based on the principles of the EMF (2019), life cycle impact indicators belong to complementary impact indicators, which are indicators that can be used alongside the MCI to assess how changing the level of material and product circularity affects other impacts of interest to businesses, their stakeholders, and the environment. In this research, these indicators are comparable to MCI in a graphical representation (Table 1) which is specific for a single environmental life cycle impact category (whose score is reported on the X-axis) and aims to represent an innovative interpretation panel through which to prioritize circularity actions based on successive impacts that can be important to the environment.

To prove whether applying circular principles can improve or worsen the environmental impacts of products, two products are compared: product A is the less circular, and product B is the more circular. Each point in the graph represents the circular and environmental performance of the product analyzed (e.g., product A) which can be linked to another comparable product (e.g., product B) through a trend line whose:

- SENSE of reading is from product A to product B.
- SLOPE represents the prevailing direction towards improving/worsening of the performances.
- LENGTH quantifies the improvement/worsening magnitude (i.e., the longer the trend line, the higher the variation of the circular environmental performances between product A and product B).

The authors expect to detect several scenarios in which circularity may lead to both an increase and a worsening of environmental impacts. These scenarios could probably be influenced by each environmental impact category and the different contexts of the coupled products evaluated. The relationship between MCI and environmental LCIA scores is expected to be compatible, as both derive from the same inventory data. Therefore, the trend line (and its characteristics) of the compared products may represent an indicator through which to better interpret their comprehensive circular-environmental assessments.

2.2 Description of case studies

A multiple case study method was carried out to expand the theoretical knowledge of the integrated model developed by integrating new empirical insights derived from real-world cases (Yin 2018) and therefore to validate the integrated model developed. The agri-food sector was defined as suitable for this study since its products encompass both biological and technical materials. Two versions of the same product made by the same company producer were identified and compared within the integration model to analyze their circular and environmental performance.

- Organic version (ORG) originating from organic production intended as an overall system of farm management and food production that combines best environmental practices, an elevated level of biodiversity, the preservation of natural resources, the application of high animal welfare standards, and a production method in line with the preference of certain consumers for products produced using natural substances and processes. The organic production method delivers public goods that contribute to the protection of the environment and animal welfare, as well as to rural development (EUR-LEX 2018).
- Non-organic version (NON-ORG) originating from the conventional production chain without considering organic standards.

Agri-food products considered case studies are shown in Table 2. All case studies in the literature belonged to the International EPD® System Programme except for the Rigoni jam case, which was a real study carried out by the authors in collaboration with the company producer. More case studies were selected to assess the generality of the method and its application in different contexts.

3 Results

3.1 Goal and scope definition

The goal of the LCA of each compared case study is to gather useful results for the analysis and contextualization of the integrated MCI-LCA method to evaluate its applicability and effectiveness. Consequently, appropriate conclusions may be drawn, possibly suggesting improvement ideas with the final goal of translating the results obtained into operational indications so that the responsible bodies (e.g., ISO Technical Committee 323 of which EMF is a contributor) can be helped implement CE strategies. The results are not intended to be used in comparative assertions intended to be disclosed to the public.

As reported in Table 3, environmental analyses of case studies were carried out using the LCA methodology according to ISO 14040 and 14044 (2006b). The processing data were primary and secondary (sourced from the Ecoinvent database) for all case studies and were processed using SimaPro software. The impact assessment results were calculated using EPD (PRé Sustainability B.V. 2022) which is a method used to create EPD according to the specific GPI and Product Category Rules (PCR). The declared units chosen were the production of one mass or volume unit of product related to each case study. The boundaries of the study system were from cradle to grave: specifically, from the procurement of raw materials and packaging, the transport of raw materials and the production of agri-food products, to their distribution, and the end of life of packaging and waste, with the exclusion of the use phase. Studies met the cut-off criteria required by the reference Product Category Rules (PCR), and data for elementary flows to and from the product system that contributed to a minimum of 99% of declared environmental impacts were included. Methodological choices for reuse, recycling, and recovery allocation were established according to the polluter pays principle (PPP) according to OECD (1972), where the waste generator must carry the full environmental impact until the point in the product life cycle at which the waste is transported to the gate of a waste processing plant (collection site). For each product from each case study, the sum of impacts of a process unit is equivalent to its total impact.

3.2 Life cycle inventory (LCI)

As reported in Sect. 2.2, the Rigoni jam case study was the only real case study that required the LCI through a specific questionnaire (Table 4). The LCI of the case studies in the remaining literature was performed upstream of the EPDs. The Rigoni jam production system was subdivided into four process units: raw material cultivation, raw material processing, jam production process, and distribution process to the logistics center.

The unit of the raw material production process did not belong to the ORG version because blueberries were harvested by hand mainly in the pristine forests of Bulgaria (no cultivation process), and therefore the quantification of the input/output was not applicable; additionally, the NON-ORG input/output of the cultivated blueberry flows was characterized by the company producer in a study using the same LCIA methodology.

3.2.1 Inventory indicators from EPD

As seen in Sect. 2.1, renewable and non-renewable primary energy resources used as raw materials and secondary raw materials are EPD indicators for the use of resources and were

Table 2 Description of case studies

Name	Rigoni jam	Molino Grassi flour	Sgambaro pasta	Monini EVO oil	Granarolo mozzarella	Fileni chicken breast
Source	Original contribution of the authors	EPD-A (2021); EPD-B (2021)	EPD-A (2022); EPD-B (2022)	EPD-C (2022); EPD-D (2022)	EPD-E (2022); EPD-F (2022)	EPD-C (2021); EPD-D (2021)
Organic version (ORG)	Made with organic wild blueberries	Made with organic durum wheat	Made with 100% Italian organic durum wheat	Made with 100% Italian organic olives	Made with 100% Italian organic milk	Made with 100% Italian organic chicken
Non-organic version (NON-ORG)	Made with cultivated blueberries	Made with durum wheat	Made with 100% Italian durum wheat	Made with olives from Italy, Spain, Portugal, and Greece	Made with 100% Italian milk	Made with 100% Italian chicken

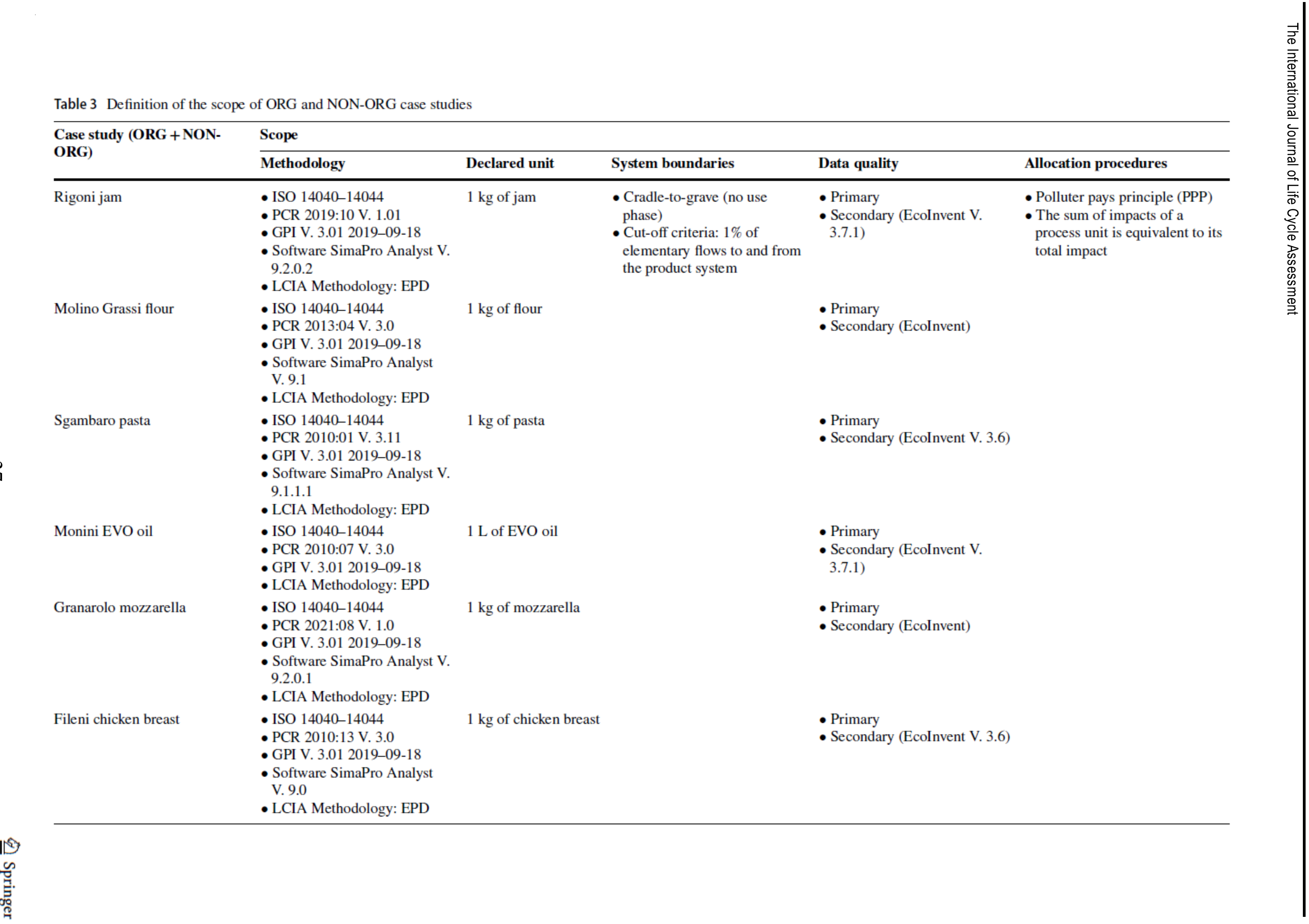


Table 3 Definition of the scope of ORG and NON-ORG case studies

Case study (ORG + NON-ORG)	Scope				
	Methodology	**Declared unit**	**System boundaries**	**Data quality**	**Allocation procedures**
Rigoni jam	• ISO 14040–14044 • PCR 2019:10 V. 1.01 • GPI V. 3.01 2019–09-18 • Software SimaPro Analyst V. 9.2.0.2 • LCIA Methodology: EPD	1 kg of jam	• Cradle-to-grave (no use phase) • Cut-off criteria: 1% of elementary flows to and from the product system	• Primary • Secondary (EcoInvent V. 3.7.1)	• Polluter pays principle (PPP) • The sum of impacts of a process unit is equivalent to its total impact
Molino Grassi flour	• ISO 14040–14044 • PCR 2013:04 V. 3.0 • GPI V. 3.01 2019–09-18 • Software SimaPro Analyst V. 9.1 • LCIA Methodology: EPD	1 kg of flour		• Primary • Secondary (EcoInvent)	
Sgambaro pasta	• ISO 14040–14044 • PCR 2010:01 V. 3.11 • GPI V. 3.01 2019–09-18 • Software SimaPro Analyst V. 9.1.1.1 • LCIA Methodology: EPD	1 kg of pasta		• Primary • Secondary (EcoInvent V. 3.6)	
Monini EVO oil	• ISO 14040–14044 • PCR 2010:07 V. 3.0 • GPI V. 3.01 2019–09-18 • LCIA Methodology: EPD	1 L of EVO oil		• Primary • Secondary (EcoInvent V. 3.7.1)	
Granarolo mozzarella	• ISO 14040–14044 • PCR 2021:08 V. 1.0 • GPI V. 3.01 2019–09-18 • Software SimaPro Analyst V. 9.2.0.1 • LCIA Methodology: EPD	1 kg of mozzarella		• Primary • Secondary (EcoInvent)	
Fileni chicken breast	• ISO 14040–14044 • PCR 2010:13 V. 3.0 • GPI V. 3.01 2019–09-18 • Software SimaPro Analyst V. 9.0 • LCIA Methodology: EPD	1 kg of chicken breast		• Primary • Secondary (EcoInvent V. 3.6)	

Table 4 Life cycle inventory of the Rigoni jam case study

Rigoni jam LCI					
Process unit	**Input/ Output (I/O)**	**Description**	**Unit**	**ORG**	**NON-ORG**
Raw material farming	I I I O	Diesel Water Pesticides and fertilizer Waste	kg CO2 eq kg SO2 eq kg PO4–- eq kg NMVOC eq kg Sb eq MJ, net calorific value m3 eq	– – – – – – –	9.47E-02 1.02E-03 1.26E-03 5.69E-04 4.71E-07 1.76E + 00 3.03E + 00
Raw material processing	I	Transport	t*km	4.64E-01	
	I	Blueberries	kg	1.03E + 00	
	I	Plastic-paper bags	kg	1.30E-03	
	I	Plastic bags (blue food plastic)	kg	1.08E-03	
	I	Washing water	L	5.43E + 00	
	I	Natural gas	m3	3.85E-05	
	I	Public electricity	KWh	4.71E-01	
	O	Paper	kg	6.37E-03	
	O	Plastic materials	kg	8.74E-04	
	O	Fruit processing waste	kg	2.56E-02	
Jam production process	I	Transport	t*km	8.39E-01	
	I	Blueberries	kg	5.56E-01	
	I	Water	m3	1.50E-03	
	I	Natural gas	m3	9.46E-02	
	I	Public electricity	KWh	2.86E-02	
	O	COD	–	8.24E-03	
	O	BOD	–	1.65E-02	
	O	Plastics CER 15.01.02	kg	1.32E-03	
	O	Paper and cardboard 15.01.01	kg	1.11E-03	
Distribution process to logistics center	I	Transport	t*km	1.37E-01	
	I	Pallet	kg	2.25E-03	
	O	Polyethylene extensible film (all sizes)	kg	1.20E-03	

used, along with primary raw materials, to characterize the feedstock flows for the MCI calculation. All these indicators mainly concerned the upstream stage of packaging production.

Similarly, hazardous and nonhazardous waste disposed, radioactive waste disposed, components for reuse, material for recycling, and materials for energy recovery are EPD indicators for waste and output flows, which were exploited as destination after use flows (Table 5).

3.3 Circularity assessment

In the comparison of case studies, all ORG case studies achieved circular performances better than NON-ORG (Table 6) mainly due to the use of organic fertilizers for raw material production set at 95% as the minimum percentage for the product to be considered organic (EU 2022d). Consequently, less relevant technical cycles were detected in the form of reduced use of virgin materials ($V_{ORG} < V_{NON\text{-}ORG}$). The LFI values (as the quantification of V ending up as W attributed to the product) diverged significantly between ORG and NON-ORG case studies because of the differences in the V values. The *W* values, on the other hand, were quite similar for all the case studies compared. Circularity Δmax (0.55) was achieved by the Molino Grassi flour case study in the ORG-NON-ORG comparison.

3.4 Life cycle impact assessment (LCIA)

The purpose of the Life Cycle Impact Assessment is to highlight the number of environmental changes that are generated due to releases into the environment (emissions or waste) and the consumption of resources associated with a product. Table 7 shows the LCIA indicators for each case study.

Table 5 Inventory indicators from EPD

	Inventory indicators from EPD	**Case studies**												
		Unit	Rigoni jam		Molino Grassi flour		Sgambaro pasta		Monini EVO oil		Granarolo mozzarella		Fileni chicken breast	
			ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG
Feedstock	Renewable primary energy resources—used as raw materials	MJ	5.00E-01	5.00E-01	1.38E-01	9.22E-02	4.78E-01	4.41E-01	4.94E-01	3.12E-01	4.00E-01	2.90E-01	7.52E-02	7.28E-02
	Non-renewable primary energy resources—used as raw materials	MJ	2.77E-01	2.77E-01	–	–	1.40E-02	1.40E-02	8.50E-03	3.51E-02	2.70E+00	2.20E+00	5.12E-01	2.40E-01
	Secondary raw material	kg	–	–	–	–	–	–	1.76E-01	1.76E-01	2.10E-01	1.50E-01	4.38E-02	4.24E-02
Destination after use	Hazardous waste disposed	kg	5.99E-03	1.06E-02	–	3.92E-08	1.30E-05	1.30E-05	–	–	6.80E-04	5.70E-04	3.20E-04	1.54E-04
	Nonhazardous waste disposed	kg	5.99E-03	1.06E-02	–	6.10E-04	1.19E-01	1.18E-01	–	–	7.60E-02	6.60E-02	6.01E-02	9.89E-02
	Radioactive waste disposed	kg	5.99E-03	1.06E-02	–	–	1.00E-06	1.00E-06	2.70E-04	2.64E-04	7.60E-04	4.10E-03	2.84E-05	3.12E-10
	Components for re-use	kg	1.83E-02	1.37E-02	–	–	–	–	–	–	–	–	7.10E-01	5.56E-01
	Material for recycling	kg	1.83E-02	1.37E-02	8.09E-03	5.43E-03	5.00E-03	5.00E-03	2.56E-01	2.46E-01	3.70E-01	2.60E-01	1.13E-01	1.57E-01
	Materials for energy recovery	kg	–	–	7.51E-04	4.40E-04	–	–	–	–	2.50E-02	2.50E-02	–	–

Table 6 Calculation of the material circularity indicator of case studies

MCI circularity assessment	**Case studies**											
	Rigoni jam		Molino Grassi flour		Sgambaro pasta		Monini EVO oil		Granarolo mozzarella		Fileni chicken breast	
	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG
Virgin feedstock (V)	0.07	0.94	0.05	1.00	0.05	0.99	0.05	0.97	0.06	0.98	0.06	0.98
Unrecoverable waste (W)	0.54	0.54	0.26	0.32	0.87	0.87	0.25	0.27	0.37	0.38	0.16	0.21
Linear Flow Index (LFI)	0.32	0.77	0.17	0.72	0.46	0.93	0.17	0.69	0.24	0.74	0.11	0.61
Material Circularity Indicator (MCI)	0.68	0.23	0.83	0.28	0.54	0.07	0.83	0.31	0.76	0.26	0.89	0.39

Table 7 Life cycle impact category scores from case studies

LCIA category	Unit	**Case studies**											
		Rigoni jam		Molino Grassi flour		Sgambaro pasta		Monini EVO oil		Granarolo mozzarella		Fileni chicken breast	
		ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG
GWP	kg CO2 eq	1.32E+00	1.64E+00	3.02E-01	3.22E-01	5.22E-01	7.96E-01	3.34E+00	4.15E+00	7.49E+00	9.38E+00	4.22E+00	2.95E+00
AP	kg SO2 eq	1.56E-02	2.16E-02	6.69E-03	5.50E-03	4.02E-03	1.15E-02	2.54E-02	4.38E-02	1.64E-01	1.25E-01	7.15E-02	4.53E-02
EP	kg PO43- eq	7.95E-03	9.85E-03	3.10E-03	3.90E-03	2.46E-03	7.08E-03	4.70E-03	3.36E-02	6.30E-02	4.11E-02	5.09E-02	2.91E-02
POFP	kg NMVOC eq	4.22E-03	4.22E-03	2.22E-03	1.46E-03	2.91E-03	3.00E-03	2.96E-02	2.70E-02	2.00E-02	1.76E-02	1.29E-02	7.05E-03
ADP-E	kg Sb eq	8.51E-06	8.91E-06	7.74E-08	1.71E-06	5.90E-06	1.21E-05	2.51E-06	1.91E-04	4.48E-06	2.31E-06	2.79E-06	2.51E-06
ADP-FF	MJ	1.50E+01	1.70E+01	3.70E+00	2.91E+00	7.06E+00	7.67E+00	4.80E+01	4.49E+01	5.34E+01	6.09E+01	2.85E+01	2.27E+01
WSF	m3 eq	8.99E-01	2.21E+00	6.37E-01	6.46E-01	1.76E+00	1.54E+00	4.38E-01	3.28E+01	1.15E+01	1.06E+01	8.22E+00	1.04E+01

The environmental performance of the ORG case studies was better than those of NON-ORG for Rigoni jam with all life cycle impact categories except POFP; Molino Grassi flour with GWP, EP, ADP-E, and WSF scores; Sgambaro pasta with all life cycle impact categories except WSF; and Monini EVO oil with GWP, AP, EP, ADP-E, and WSF scores. However, the ORG case studies with poorer environmental performance than NON-ORG were Fileni chicken breast with GWP, AP, EP, POFP, ADP-E, and ADP-FF scores and Granarolo mozzarella with AP, EP, POFP, ADP-E, and WSF scores.

The life cycle impact category that showed better scores for ORG case studies than for NON-ORG was GWP (5 out of 6 ORG case studies): this is probably because the carbon of ORG released in the atmosphere does not contribute to increasing the concentration of CO_2 but is reabsorbed with the regeneration of vegetation, making its contribution neutral to the greenhouse effect. The kinetics of carbon transfer from the plant compartment to the atmosphere is assumed to be equal to that of the reverse passage.

The worst life cycle impact category for ORG case studies was POFP (1 out of 6 ORG case studies): it is the formation of reactive substances (mainly ozone) that are harmful to human health and ecosystems. In a contaminated environment, the maximum concentration of ozone is determined by the absolute amounts of volatile organic compounds and nitrogen oxides (NOx). The low availability of nitrogen oxides in rural areas, such as those used to produce raw material in ORG case studies, limits the generation of ozone. However, summer circumstances improve ozone creation due to increased UV light, low wind speeds, and stagnation conditions, as well as increased precursor emissions, such as nitrogen oxides from soils and larger amounts of volatile organic compounds (WHO Regional Office for Europe 2000).

Since life cycle impact category scores are relative values based on samples under analysis, it is necessary to populate more and more literature data on different product categories as reference values for environmental performance. An example of effective and internationally recognized communication is that of the EPD (based on ISO 14025 and ISO 14040–14044) which, as demonstrated in this study, can be exploited as a support tool for the circularity assessment (Sect. 3.3) and the LCIA phase.

Normalization processing was performed for all LCIA indicators (Table 8) to relate their measurement to standard references (set at the maximum value of internal data).

Figure 1 shows the contribution analysis of case study processes identified according to the case study-specific PCR (Table 3) and depending on the position in the production chain: upstream (U) regarding raw material and/or packaging, core (C) about raw material transport and/or product processing, and downstream (D) on distribution and end of life of packaging and/or wastes.

Table 8 Normalized life cycle impact category scores of case studies

LCIA category	Unit	**Case studies**											
		Rigoni jam		Molino Grassi flour		Sgambaro pasta		Monini EVO oil		Granarolo mozzarella		Fileni chicken breast	
		ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG	ORG	NON-ORG
GWP	–	0.14	0.17	0.03	0.03	0.06	0.08	0.36	0.44	0.80	1.00	0.45	0.31
AP	–	0.10	0.13	0.04	0.03	0.02	0.07	0.15	0.27	1.00	0.76	0.44	0.28
EP	–	0.13	0.16	0.05	0.06	0.04	0.11	0.07	0.53	1.00	0.65	0.81	0.46
POFP	–	0.14	0.14	0.08	0.05	0.10	0.10	1.00	0.91	0.68	0.59	0.44	0.24
ADP-E	–	0.04	0.05	0.00	0.01	0.03	0.06	0.01	1.00	0.02	0.01	0.01	0.01
ADP-FF	–	0.25	0.28	0.06	0.05	0.12	0.13	0.79	0.74	0.88	1.00	0.47	0.37
WSF	–	0.03	0.07	0.02	0.02	0.05	0.05	0.01	1.00	0.35	0.32	0.25	0.32

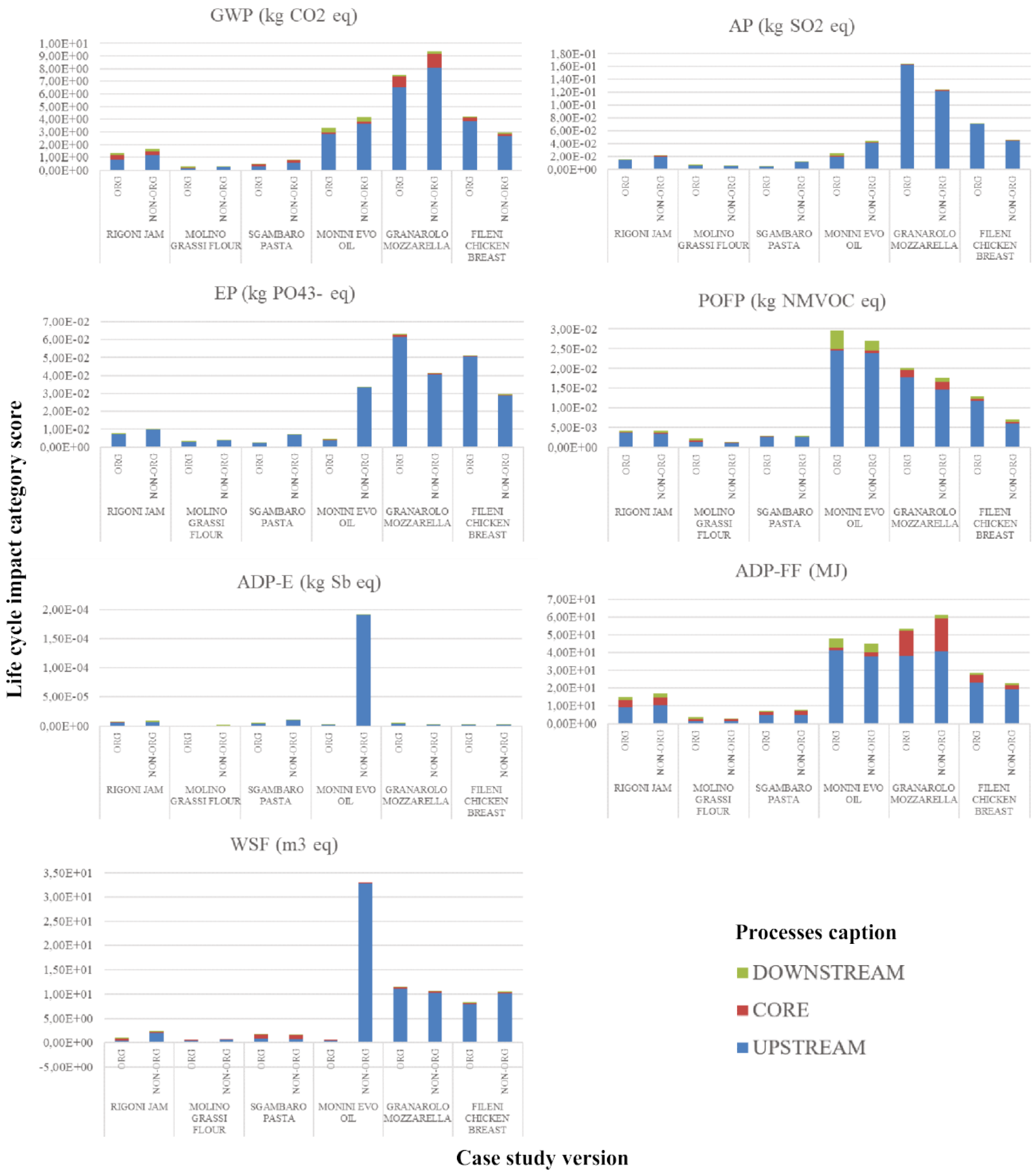


Fig. 1 Contribution analysis of case study processes

ORG case studies resulted in higher total environmental impacts than NON-ORG ones for the following life cycle impact categories:

- GWP of Fileni chicken breast due to U-C-D processes
- AP due to the U-C-D processes for both Molino Grassi flour and Fileni chicken breast and the U process for Granarolo mozzarella
- EP due to U-C processes for Granarolo mozzarella and U-D processes for Fileni chicken breast

- POFP due to U-C-D processes for both Molino Grassi flour and Fileni chicken breast, U-D processes for Monini EVO oil, and U processes for Granarolo mozzarella
- ADP-E of Granarolo mozzarella due to U-C processes and U-C-D processes for Fileni chicken breast
- ADP-FF due to U-D processes for Monini EVO oil, U-C-D processes for Fileni chicken breast, and C-D processes for Molino Grassi flour
- WSF of Sgambaro pasta and Granarolo mozzarella due to U-D processes

Generally, ORG case studies were more environmentally impactful than NON-ORG cases due to U processes in all case studies, except Molino Grassi flour ADP-FF, and likewise NON-ORG case studies were more environmentally impactful due to U processes for all case studies. Therefore, the U processes played a key role in contributing to the overall environmental impacts. With reference to the single LCIA category:

- GWP, AP, POFP: the highest air emissions of CO_2, SO_2, and NMVOC (photochemical smog) air emissions were related to the production and consumption of fuel for the cultivation and transport of raw materials, the production of packaging, and any energy production and consumption (such as electricity and natural gas) for the processing of raw materials.
- EP: the greatest PO_4^{3-} impacts for the vegetal case studies (Rigoni jam, Molino Grassi flour, Sgambaro pasta, and Monini EVO oil) were probably related to nutrient emissions (N/P) caused by organic fertilizers. For animal case studies (Granarolo mozzarella and Fileni chicken breast), the higher impacts of the ORG versions are related to the longer chicken rearing period (83 vs 43 days) and to lower yields (85%) of bovine reared according to organic standards (Bilik and Lopuszanska-Rusek 2010; Müller and Sauerwein 2010; Stiglbauer et al. 2013).
- ADP-E, ADP-FF: the emissions of these categories are related to the extraction of minerals and fossil fuels due to the input of the system, such as the production of fuels for the cultivation and transport of raw materials, the production of pesticides and fertilizers, the production of packaging, and any production of energy sources for the processing of raw materials.
- WSF: the highest water consumption for vegetal case studies was related to the farming and processing of vegetable crops and to the watering of chickens and bovines and washing processes during their farming period.

The significant difference in the impact of ADP-E and WSF between the ORG and NON-ORG versions of Monini EVO oil is probably due to the different cultivation practices applied in the geographical locations of olive production (Italy for ORG vs Spain, Portugal, and Greece for NON-ORG) along with the application of organic production standards, which contributed to reduce mineral losses and water consumption.

Specifically for the vegetal case study group, ORG versions showed better environmental performances than NON-ORG ones due to the application of the organic production method for the GWP, AP, EP, and ADP-E LCIA categories.

From an overview of all life cycle impact categories, it is possible to observe higher generalized values for Monini EVO oil, Granarolo mozzarella, and Fileni chicken breast than the remaining case studies in 6 out of 7 LCIA categories.

3.5 Interpretation of results

Figure 2 represents the interpretation of results of case studies specific for the environmental impact category detected in Sect. 2.1.

As reported in Sect. 3.3, all ORG products are more circular than NON-ORG products for all LCIA categories, and this is represented in Fig. 2 by the green dots located at the top of each trend line. The overall LCIA normalized score Δmax (0.99) between ORG and NON-ORG case studies emerged in Monini EVO oil in the ADP-E impact category, and it is represented by the longest lines on the graphs. The graphical profiles of Monini Grassi flour, Granarolo mozzarella, and Fileni chicken breast in the ADP-E impact category are very close together due to their different order of magnitude (E-06) than ORG Monini EVO oil (E-04). In all remaining life-cycle impact categories, the variability of the impact values never exceeded E01.

ORG case studies that showed higher LCIA scores than those of NON-ORG were represented with a trend line slope between 0 and 90°, while those that showed lower LCIA scores than those of NON-ORG were represented with a trend line slope between 90 and 180°. Therefore, from a careful examination of the several graphical representation patterns of Fig. 2, it is possible to detect five scenarios for the circular-environmental assessment of compared products (Table 9) depending on the slope (S) and length of trend line and is valuable when the reading senses of trend lines are from the less circular to the more circular product.

Scenario no. 1 was detected in the following compared products:

- Fileni chicken breast in the EP LCIA categories.
- Granarolo mozzarella in the AP and EP LCIA categories.

Scenario no. 2 was detected in the following compared products:

- Molino Grassi flour in the AP, POFP, and ADP-FF LCIA categories.

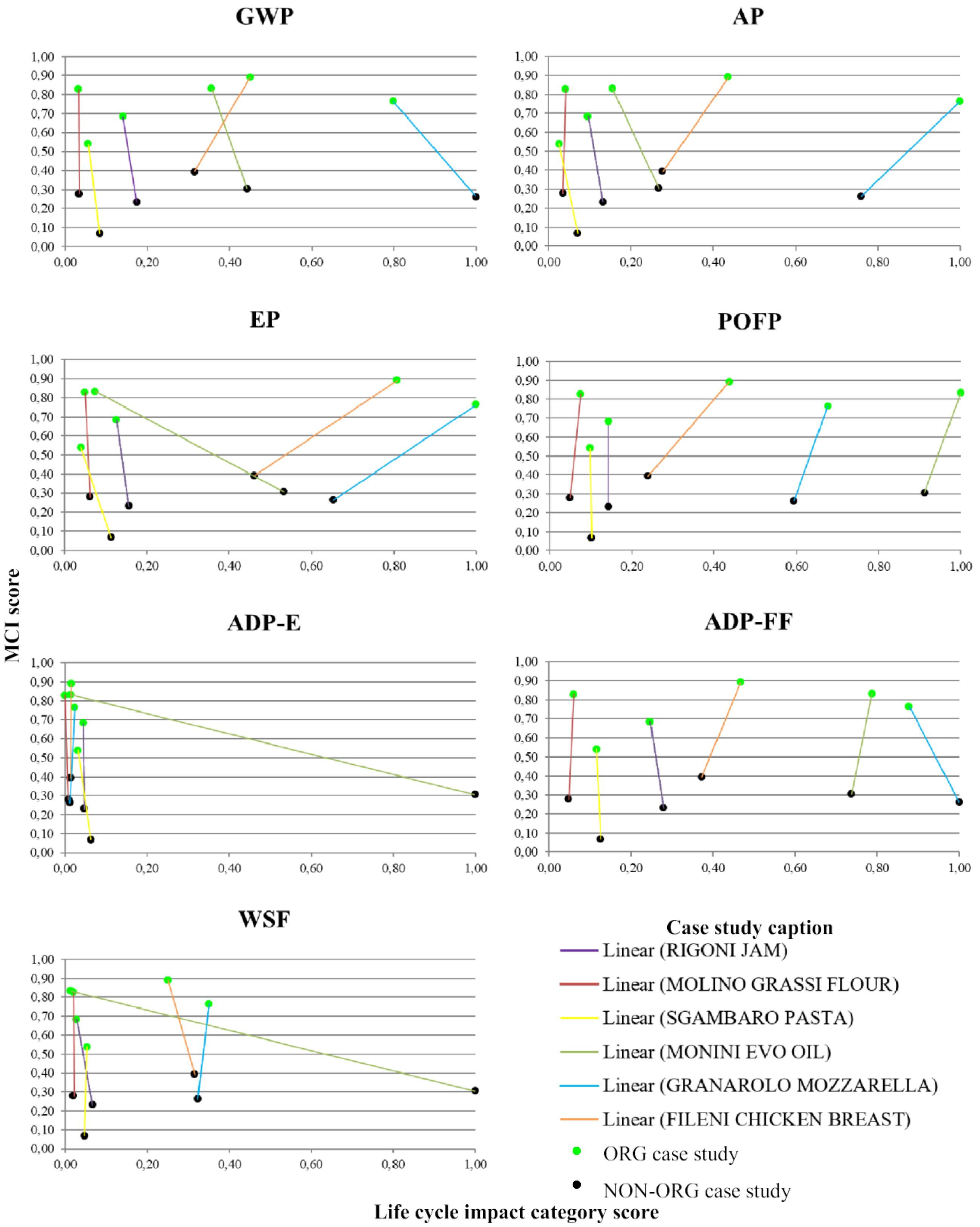


Fig. 2 Interpretation of results of case studies

Table 9 Circular-environmental assessment scenarios of compared products

Scenario no	Trend line slope (S)	Interpretation	Circular-environmental assessment
1	0° < S ≤ 45°	Circularity increases less significantly than environmental impact	The higher is the circularity, the higher are environmental impacts
2	45° < S < 90°	Circularity increases more significantly than environmental impact	
3	S = 90°	Circularity increases significantly, while environmental impact is constant	Circularity does not affect environmental impacts
4	90° < S ≤ 135°	Circularity increases significantly, while environmental impact decreases gradually	The higher is the circularity, the lower are environmental impacts
5	135°<S ≤ 180°	Circularity increases gradually while environmental impact decreases significantly	

- Monini EVO oil in the POFP and ADP-FF LCIA categories.
- Granarolo mozzarella in the POFP, ADP-E, and WSF LCIA categories.
- Fileni chicken breast in the GWP, AP, POFP, and ADP-FF LCIA categories.

Scenario no. 3 was detected in the following compared products:

- Molino Grassi flour in the GWP and WSF LCIA categories.
- Rigoni jam in the POFP LCIA categories.
- Sgambaro pasta in the POFP and WSF LCIA categories.
- Fileni chicken breast in the ADP-E LCIA categories.

Scenario no. 4 was detected in the following compared products:

- Rigoni jam in the GWP, AP, EP, ADP-E, ADP-FF, and WSF LCIA categories.
- Molino Grassi flour in the EP and ADP-E LCIA categories.
- Sgambaro pasta in the GWP, AP, EP, ADP-E, and ADP-FF LCIA categories.
- Monini EVO oil in the GWP and AP LCIA categories.
- Granarolo mozzarella in the GWP and ADP-FF LCIA categories.
- Fileni chicken breast in the WSF LCIA categories.

Scenario no.5 was detected in the following compared products:

- Monini EVO oil in the EP, ADP-E, and WSF LCIA categories.

The most detected scenarios were the no. 4 (eighteen trend lines) in which circularity increases significantly while environmental impact decreases gradually, and the no. 2 (twelve trend lines) in which circularity increases more significantly than environmental impact. Scenario nos. 1 and 5 were the least detected with three trend lines each. Scenario nos. 1 and 2 (i.e., where circularity led to higher environmental impacts) were detected in 5 out of 7 LCIA categories of Granarolo mozzarella and Fileni chicken breast; scenario no. 3 (i.e., where circularity did not affect environmental impacts) was detected in 2 out of 7 LCIA categories of Molino Grassi flour and Sgambaro pasta; scenario nos. 4 and 5 (i.e., where circularity led to lower environmental impacts) were detected in 6 out of 7 LCIA categories of Rigoni jam.

As argued in Sect. 1, CE appears to be one of the most topical debated topics due to a slew of regulations and directives enacted at both the European and global levels and leading to several financial initiatives that encourage the manufacturing system to adopt CE models to reduce its environmental impact. Therefore, in the different circular-environmental assessments resulting from trend line slopes, scenario nos. 4 and 5 seem to be the most preferred, and the fact that the scenario no. 4 resulted as the most detected encourages the implementation of even more circular-environmental practices. Applying the proposed integrated method to more compared case studies could certainly be of interest for the detected circular-environmental scenarios to be considered general or sector guidelines for the integrated circular-environmental assessment of products and try to bridge the gap of standardized regulations on CE measurement framework, which have led to the current nonuniform indicator approaches. Technical Committee ISO/TC 323 on CE (International Organization for Standardization/Technical Committees 323 2021) could represent a possible answer to this issue (Rigamonti and Mancini 2021), also thanks to its collaboration with the EMF itself.

4 Discussion

In the modeling to determine MCI (Sect. 2.1), flows about biological circular cycles are represented by sustained biological feedstock and product to composting flow.

The biological feedstock from Sustained Production was assumed to be present in the primary biological raw materials of organic products. Proving that biological feedstock derives from a Sustained Production can be challenging (EMF 2019) also because there are still no universally recognized metrics and methodologies that can quantify the yields and cascades of value of sustained biological materials, and that characterize their ability to degrade in the biosphere (Haas et al. 2020; Navare et al. 2021). However, this research wanted to get the hint from the EMF by determining the sustained biological feedstock in the primary biological raw materials of organic products, thanks to the contact points between the EMF methodology (2019) and the EU organic definition (EUR-LEX 2018) about limiting the use of non-renewable resources and developing healthy soils. This principle is assumed to be true because it provides the starting point of a theoretical framework of reference to be validated with further case studies concerning circular biological cycles. On the other hand, the product to composting flow was assessed for both organic and non-organic products and set at the EU average percentage (11%) of municipal food waste composted in 2020 to give concreteness to the process of natural systems regeneration of biological cycles. Since it is also possible to rely on the update of existing indicators (Navare et al. 2021), the MCI Dynamic Modelling Tool (2015) was reviewed in which, according to the EMF methodology, the biological feedstock flow was added in the Feedstock section and the product streams to composting and to energy recovery in the destination after use section.

Uncertainties in datasets could represent an issue when comparing different LCA studies of coupled products based on different PCR and GPI. In the specific context of this research, all EPDs of each of the coupled case studies were performed according to the same PCR and GPI (Sect. 3.1) since they belonged to the same company producer. In a wider perspective, more coupled products belonging to the agri-food sector were compared, and all their EPDs were executed with the same GPI (EPD International AB 2019) while keeping the same LCA requirements. Normalized data (Sect. 3.4) could represent a limitation since only two decimal places are considered for the result interpretation, and minimal value variations might miss. However, since this research also aims to assess a general overview of the circular-environmental performances of compared products within the proposed integrated model, this aspect could be neglected.

Limitations in MCI calculation may be represented by not including either energy flows (Rufí-Salís et al. 2021) or transportation (Saidani et al. 2019), even though they are counted in the LCIA. In Sect. 3.2.1, secondary raw materials were counted together with renewable primary energy resources—used as raw material (by converting their flows from MJ to kg) as circular flows in the MCI calculation. Therefore, an innovative element in the feedstock flow modeling of the EMF methodology (2019) was introduced in which any circular variation of the energy consumption related to raw materials can be related to the MCI, while energy carrier resources remained excluded. In the specific context of this study, it is assumed that the transportation processes of all case studies had linear patterns that were impossible to quantify in a circular perspective like that of the MCI dynamic modeling tool (2015). It is assumed that the efficiency of the recycling process used for the portion of a product collected for recycling is constant for all case studies (at 49% as reported in Sect. 2.1). This assumption allowed highlighting and comparing the material for recycling flows of each case study under the same recycling conditions. It was necessary because of the lack of data and since data collection for this purpose is a long and complex process due to the quantity of materials and elements (Rufí-Salís et al. 2021).

It has to be recognized that the integrated methodology presented in this study and its encouraging results on improving environmental performance in conjunction with circular practices (Sect. 3.5) could be misled due to the presence of rebound effects (André and Björklund 2022). These concern the environmental impacts related to the application of CE principles, which, although negative with respect to a single product system, to a larger scale involving product systems in close proximity are positive (Zink and Geyer 2017). The poor availability of accurate data on product use and user behavior makes it difficult to perform more extensive evaluation in the current circular-environmental assessments (Harris et al. 2021). Despite the unpredictable nature of highly complex market systems strictly related to the presence of rebound effects, wide-ranging efforts among circular and environmental experts are desirable to produce products and materials that truly are substitutes for primary production alternatives, brake/reduce aggregate demand for goods, and draw consumers away from primary production (Zink and Geyer 2017).

Comparing the integrated model presented in this study with agri-food studies in the literature that used MCI and LCA (Sect. 1), Rocchi et al. (2021) tried to put the information together and compare the results without having an overall view of the circular and environmental performances of poultry production. Niero and Kalbar (2019) coupled materials circularity-based indicators (including MCI) and life cycle-based indicator (including LCA) via Multi-criteria Decision Analysis applied to beer packaging (and therefore focusing only to the technical circular cycles) in the UK and Indian markets as a support for the harmonic integration of different circular perspectives. Rufi-Salìs et al. (2021) developed an innovative formula which makes the product of the MCI score with the specific life cycle impact category score to achieve an integrated circular and environmental score comparable with several scenarios of urban agriculture in histogram charts. Undoubtedly, the latter study shows similarities with this research in representing one environmental indicator at a time through a graph that allows comparisons of circular-environmental performance between different products/scenarios. In particular, Rufí-Salís et al.'s (2021) study evaluates each scenario individually, while this article presents a more exclusive representation as it has focused on the specific assessment of two products which, in turn, can be compared with other coupled products belonging to the same product category. This could represent a limitation since comparative evaluation is necessarily related to the presence of two homologous products. On the other hand, the circularity assessment of the proposed integrated model comprises the biological circular cycles according to the EMF (2019), while the determination of the MCI score in a biological context such as urban agriculture was performed according to the 2015 version of the EMF methodology which only included the technical circular cycles. Therefore, compared to studies of the current literature, the added value of the application of MCI and LCA in the integrated approach presented in this research is to allow for a comprehensive and holistic assessment through an innovative circular (both in terms of biological and technical cycles) and environmental assessment panel of coupled products (and the relative scenarios) belonging to the same product category.

Based on the dissertation of Sect. 2.1, the MCI-LCA integrated model can be considered established. What the authors expected from the principles of the interpretation of results and the results achieved in Sect. 3.5 make the model applicable. However, its effectiveness and robustness must be proven with more case studies, also to determine if eventual adjustments are required about the weighing system of technical and biological cycles (which weigh the same, according to the EMF methodology).

5 Conclusions

Literature studies have shown that there are no case studies applied to current integration models to assess whether circularity (both in terms of biological and technical cycles according to the EMF methodology (2019) means reducing environmental impacts. Therefore, based on MCI and LCA as effective circular and environmental measurement tools, respectively, the purpose of this article is firstly to propose an approach in which to apply the mentioned tools to correlate circularity with environmental impacts. Secondly, it is to test and analyze the model through compared case studies and assess its applicability as an effective product circularity-environmental assessment tool which indicates whether applying circular principles can improve or worsen the environmental impacts of products.

Case studies were detected in the agri-food sector (Sect. 2.2) since their products encompass both biologi- cal and technical materials. Based on the dissertation of Sect. 2.1, the MCI-LCA integrated model can be consid- ered established. What the authors expected from the principles of the interpretation of results and the results achieved make the model applicable. EPDs of coupled products were used as an information source for both circular (through the inventory indicators) and environmental (through the LCIA scores) evaluations since they were performed according to the same PCR and GPI, thus providing the assessment with less data uncertainties. From the examination of the graphical representation patterns of the interpretation of results phase, five scenarios for the circular-environmental assessment of the compared products were detected depending on the slope and length of the trend line and are valuable when the reading senses of the trend lines are from the less circular to the more circular product. Scenario no. 4 (in which circularity increases significantly while environmental impact decreases gradually) was the most detected and encourages the implementation of even more circular-environmental practices. Compared to studies in the current literature, the added value of the application of the MCI-LCA integrated model is to allow for a comprehensive and holistic assessment through an innovative circular (both in terms of biological and technical cycles) and environmental assessment panel of coupled products (and the relative scenarios) belonging to the same product category.

As a general outcome, applying the principles of CE did not always mean reducing the environmental impact, as it depended on the type of impact category and product. More compared case studies are required to be applied to the proposed integrated model for several reasons: firstly, to strengthen the assumption of equivalence between sustained biological feedstock and primary biological raw materials of organic products (Sects. 2.2 and 4), secondly, to determine if eventual adjustments to the weighing system of technical and biological cycles are required, and ultimately, for the detected circular-environmental scenarios to be considered general or sector guidelines for the integrated circular-environmental assessment of products and try to bridge the gap of standardized regulations on CE measurement framework, which have led to the current nonuniform indicator approaches.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no competing interests.

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4 Discussion

The results illustrated in Chapter 3 provided answers to the three research questions of the thesis. First, the most cited circular bioeconomy and environmental impact assessment tools were identified. Second, an analysis of the literature integration/combination models between circularity and environmental assessments was performed and, as results, two integration/combination models were identified. Third, the methodological feasibility and practical applicability of the circular-environmental integrated method could be shown by the method development performed by integrating the LCA approach and MCI methodology and by the application to several case studies. The findings concerning the development and application of the MCI-LCA integrated method (Section 3.3.1) are discussed in the following from an overarching perspective. Section 4.1 evaluates the overall performance of the MCI-LCA integrated method against specific criteria partly inspired and adapted from previous frameworks developed for evaluating impact assessment methods, and with regard to the intrinsic and development-related limitations of the method. A separate in-depth discussion of the development and application of the MCI-LCA integrated method is included in the paper presented in Chapter 3.3.

4.1 Performance of the MCI-LCA integrated method

In this section, the performance of the MCI-LCA integrated method is evaluated. In the first part (4.1.1), methodological and conceptional advances reached by the results displayed in Section 3.3.1 are evaluated against specific criteria partly inspired and adapted from previous frameworks developed for evaluating impact assessment methods. The second part (4.1.2) is dedicated to the intrinsic and development-related limitations of the MCI-LCA integrated method.

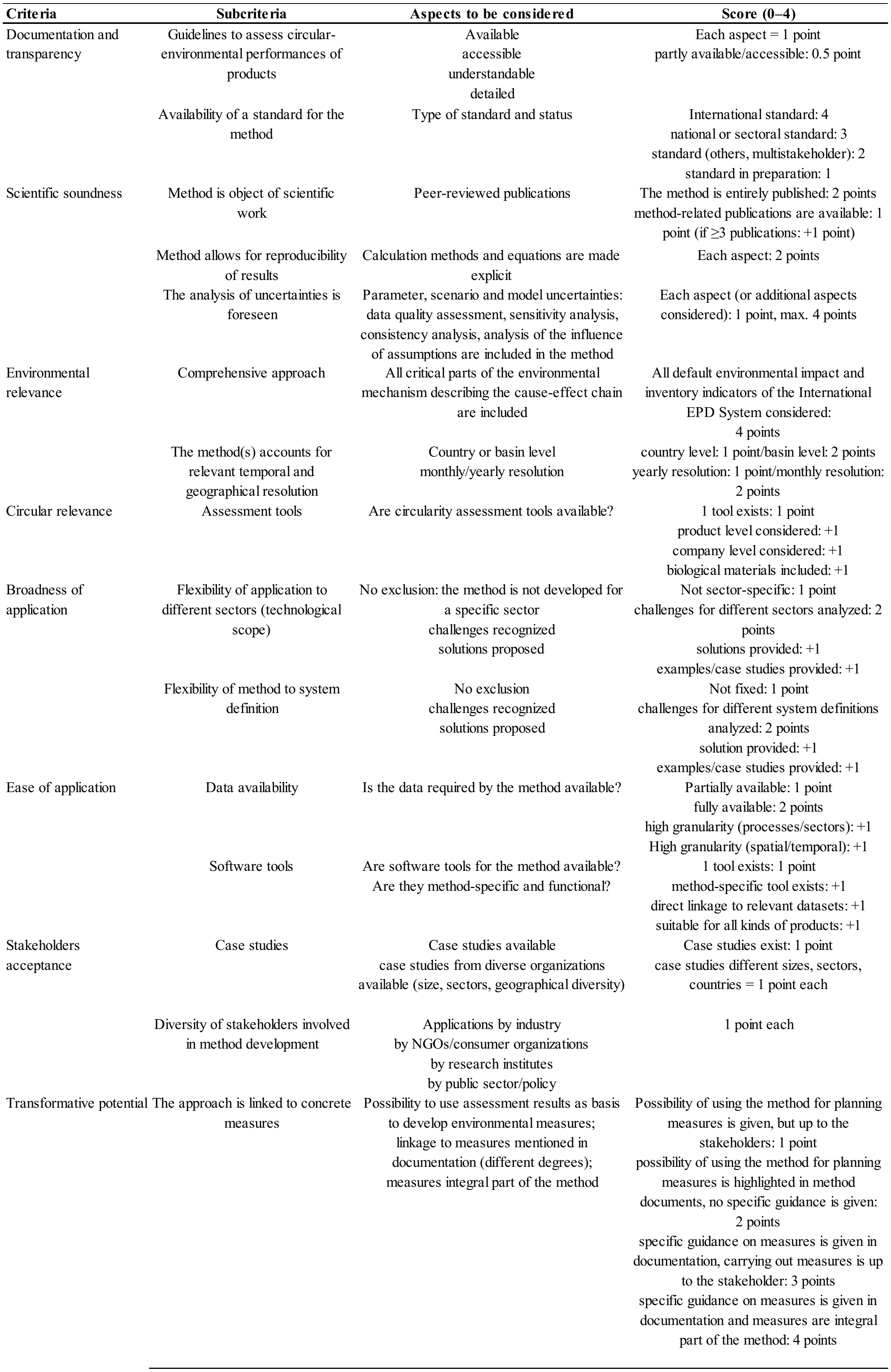
4.1.1 Evaluation of the MCI-LCA integrated method

According to the overall aim of the thesis, eight overarching evaluation criteria were identified partly inspired and adapted from previous frameworks developed for evaluating impact assessment methods (Reimann et al., 2010; Hauschild, 2010; Forin et al., 2018): 1) documentation and transparency, 2) scientific soundness, 3) environmental relevance, 4) circular relevance, 5) broadness of application, 6) ease of application, 7) stakeholder acceptance, and 8) transformative potential. Each criterion is specified by one or more subcriteria. To provide a clear overview of methods' performance, each subcriterion is attributed a score (from 0: criterion not met to 4: criterion met). The aim of the scores is to analyze the main patterns of the developed integrated method according to the given criteria and to draw conclusions for further improvement. Precise indications on rating the approaches in relation to each subcriterion are delivered in Figure 4.1.

Documentation and transparency

This criterion refers to the characteristics of documentation (guidelines) for assess the circular-environmental performances of products, and to the availability of a standard document. A document qualifies as guidance if it contains "unanimous instructions for the application by providing a widely accepted set of rules defining how the specific […] method is to be conducted." (Reimann et al., 2010). Easy accessibility of the documents is crucial for quality assurance because it allows uniform application by practitioners, third party reviews and scientific work. The availability and accessibility of methodological guidelines are evaluated based on web search.

The third publication (Gallo et al., 2023) provides detailed guidance on how to integrate the LCA environmental impact indicators with the MCI, thus enhancing the level of detail of method documentation. Additionally, it adds a demonstration that leads through the different phases of the MCI-LCA integrated method applied to several case studies with relative explanations and comments. Also, the already existing EMF methodology on MCI (EMF, 2019), ISO standard on LCA (ISO, 2006a; ISO, 2006b), and the related annexes are complemented by the discussion and recommendations on conflicting requirements, thus ensuring clarity, and allowing a straightforward application.



Criteria	Subcriteria	Aspects to be considered	Score (0–4)
Documentation and transparency	Guidelines to assess circular-environmental performances of products	Available accessible understandable detailed	Each aspect = 1 point partly available/accessible: 0.5 point
	Availability of a standard for the method	Type of standard and status	International standard: 4 national or sectoral standard: 3 standard (others, multistakeholder): 2 standard in preparation: 1
Scientific soundness	Method is object of scientific work	Peer-reviewed publications	The method is entirely published: 2 points method-related publications are available: 1 point (if ≥3 publications: +1 point)
	Method allows for reproducibility of results	Calculation methods and equations are made explicit	Each aspect: 2 points
	The analysis of uncertainties is foreseen	Parameter, scenario and model uncertainties: data quality assessment, sensitivity analysis, consistency analysis, analysis of the influence of assumptions are included in the method	Each aspect (or additional aspects considered): 1 point, max. 4 points
Environmental relevance	Comprehensive approach	All critical parts of the environmental mechanism describing the cause-effect chain are included	All default environmental impact and inventory indicators of the International EPD System considered: 4 points
	The method(s) accounts for relevant temporal and geographical resolution	Country or basin level monthly/yearly resolution	country level: 1 point/basin level: 2 points yearly resolution: 1 point/monthly resolution: 2 points
Circular relevance	Assessment tools	Are circularity assessment tools available?	1 tool exists: 1 point product level considered: +1 company level considered: +1 biological materials included: +1
Broadness of application	Flexibility of application to different sectors (technological scope)	No exclusion: the method is not developed for a specific sector challenges recognized solutions proposed	Not sector-specific: 1 point challenges for different sectors analyzed: 2 points solutions provided: +1 examples/case studies provided: +1
	Flexibility of method to system definition	No exclusion challenges recognized solutions proposed	Not fixed: 1 point challenges for different system definitions analyzed: 2 points solution provided: +1 examples/case studies provided: +1
Ease of application	Data availability	Is the data required by the method available?	Partially available: 1 point fully available: 2 points high granularity (processes/sectors): +1 High granularity (spatial/temporal): +1
	Software tools	Are software tools for the method available? Are they method-specific and functional?	1 tool exists: 1 point method-specific tool exists: +1 direct linkage to relevant datasets: +1 suitable for all kinds of products: +1
Stakeholders acceptance	Case studies	Case studies available case studies from diverse organizations available (size, sectors, geographical diversity)	Case studies exist: 1 point case studies different sizes, sectors, countries = 1 point each
	Diversity of stakeholders involved in method development	Applications by industry by NGOs/consumer organizations by research institutes by public sector/policy	1 point each
Transformative potential	The approach is linked to concrete measures	Possibility to use assessment results as basis to develop environmental measures; linkage to measures mentioned in documentation (different degrees); measures integral part of the method	Possibility of using the method for planning measures is given, but up to the stakeholders: 1 point possibility of using the method for planning measures is highlighted in method documents, no specific guidance is given: 2 points specific guidance on measures is given in documentation, carrying out measures is up to the stakeholder: 3 points specific guidance on measures is given in documentation and measures are integral part of the method: 4 points

Figure 4.1. Evaluation scheme and scoring criteria.

Scientific soundness

This criterion considers whether the method allows for the reproducibility of results, foresees the analysis of uncertainties, and evaluates the availability of peer-reviewed method publications. The latter ensure “that the recommended indicator follows current knowledge and evidence rather than opinions, subjective or arbitrary choices, and normative assumptions.” (UNEP, 2016). To assess scientific recognition, the availability of peer-reviewed publications illustrating the whole method and the availability of method-related publications (e.g., on specific aspects of the method or method application) are considered as subcriteria. Furthermore, the reproducibility of the results and the assessment of uncertainties are considered as additional subcriteria. Results are considered reproducible if the method used and the underlying equations are made explicit in the method documentation, so that, given the same inventory data, the same results can be obtained. To evaluate the ability of the method to assess uncertainties, it is considered whether the guidance foresees that data quality and underlying assumptions of the model are made explicit and assessed. The rationale behind this subcriterion is to facilitate the interpretation of the assessment results and to guarantee its quality (Lehmann et al., 2015). While results reproducibility and uncertainty analysis are guaranteed by either ISO 14040-14044 or the integrated method, the availability of peer-reviewed method publications is fulfilled by the 3. publication of this thesis, which formally describes the methodological structure and requirements and underwent a peer review process.

Environmental relevance

The environmental relevance of an approach evaluates its comprehensiveness (i.e., whether it accounts for both quantity and quality related issues), specifically regarding product-level effects on humans, ecosystems, and resources. Moreover, the criterion addresses the inclusion of relevant temporal and geographical resolution in the assessment method(s).

In line with the principles of ISO (2006a; 2006b), either the LCA method or the MCI-LCA integrated method follows a comprehensive approach considering all critical parts of the environmental mechanism describing the cause-effect chain. Specifically, product-level effects on humans, ecosystems and resources need to be included in the assessment. LCA-related ISO standards are not prescriptive with respect to the impact assessment method to be chosen. The purpose of this research considers all default environmental impact and inventory indicators of the International EPD System as impact assessment methods; therefore expertise and additional effort are required to apply the method.

The environmental relevance criterion also considers the temporal and geographical resolution allowed by the method. The temporal and spatial resolution of inventory data is often not as high, especially if secondary data needs to be used. In such cases, the available high-resolution characterization factors cannot be applied. At the same time, the possibility of high-resolution characterization factors on the impact assessment side might encourage high-resolution primary data collection or the application of secondary data regionalization options. Environmental analyses using either the LCA or the MCI-LCA methodologies are possible starting with primary and secondary (sourced from the Ecoinvent database) processing data.

Circular relevance

The circular relevance of an approach evaluates its transition level from ‘linear’ to ‘circular’ models through the availability of circularity assessment tools. The latter is made available through the work of this thesis. The tool is specifically conceived for the circularity assessment within a broader integrated assessment, i.e., it represents one of the phases of the MCI-LCA integrated method.

Broadness of application

This criterion evaluates the method applicability to different sectors and system definitions. The application of the developed MCI-LCA integrated method is flexible to different sectors, though neither challenges nor case studies for different sectors are analyzed. The possibility to flexibly define the system under study is witnessed by the application to six different production lines.

Ease of application

The criterion ease of method application evaluates the availability of data and software tools. The data required by the MCI-LCA integrated method are available in different databases for different processes. Concerning the spatial and temporal granularity, it should be differentiated between inventory data and characterization factors. Inventory data for emissions/consumptions related to processes are available in commercial databases, mainly as annual averages and with limited spatial information. Temporal and regional granularity is higher for data underlying impact assessment methods (and consequently for characterization factors as asserted by Boulay et al. (2018) and Berger et al. (2018)), thus allowing a detailed assessment if primary data are collected with the same granularity. Besides country-level and basin-level characterization factors, future applications of the MCI-LCA integrated method might be facilitated by the availability of sub-national characterization factors. Also, different software tools for assessing the environmental aspects of the overall circular-environmental assessment of products are made available through the work of this thesis.

Stakeholders acceptance

This criterion evaluates the diversity of stakeholders involved in method development and application. The case studies using the newly developed circular-environmental assessment method have been carried out for the agri-food sector (since its products encompass both biological and technical materials) and different company sizes all located in the same country. The same work can also witness the diversity of stakeholders directly involved in method development and method testing, i.e. academia and producing companies, which testifies intermediate stakeholder acceptance. No non-governmental organizations (NGOs), consumer organizations, and public sectors were involved in method development.

Transformative potential

This criterion evaluates whether there is direct linkage between the results of the measurement or assessment and policies or instruments allowing a concrete relief for the environment. The ability to establish a direct connection to mitigation measures is the weakest point either of the MCI methodology or the LCA ISO-based method. The 3. publication tackles this issue by proposing an innovative integrated method in which the possibility of using the circular-environmental assessment panel for planning measures is highlighted. Specifically, five scenarios are detected in which the relationship between circularity and the relative environmental impacts varies according to the trend line slope linking the product analyzed to another comparable product. These scenarios may potentially support the decision-makers to assess the environmental performances of products in light of circular regulations and thus to establish and communicate specific provisions to stakeholders, and researchers to model and design circular and eco-friendly products. The applicability of these pathways is discussed in the 3. publication in which first ideas for their application in other case studies are reported to better evaluate their potential to support the decisions and to be considered as general or sector guidelines for the integrated circular-environmental assessment of products.

Overall evaluation

The research work performed within this thesis enhances the scientific knowledge towards a comprehensive and applicable framework to assess the circular-environmental impacts of products. A semi-quantitative evaluation of this progress applicable to the MCI methodology, the LCA methodology, and the MCI-LCA integrated method for the different evaluation criteria specified in this Chapter is displayed in Figure 4.2. The method developed in this thesis scored halfway between the MCI and LCA methodologies in the documentation and scientific soundness criteria through a detailed guidance that underwent a peer review process (3. publication). The broadness of application and the stakeholders' acceptance were the criteria in which the integrated method performed worse than the single methodologies due to the exclusion of a life cycle phase, the presence of sector- and country-specific case studies, and the exclusion of NGOs/consumer organizations and public sectors from the integrated method's application. The same performance as the LCA methodology was achieved in the environmental relevance and ease of application thanks to their common methodological backgrounds (which is the same reason for the equal circular performances of the developed method and MCI methodology), and the availability of data and software tools. A significant impact of the thesis is related to the linkage of the circular-environmental framework to suitable mitigation measures. Additional applications of the suggested pathways will provide the necessary empirical evidence to try to bridge the gap of standardized regulations on CE measurement framework, which has led to the current nonuniform indicator approaches.

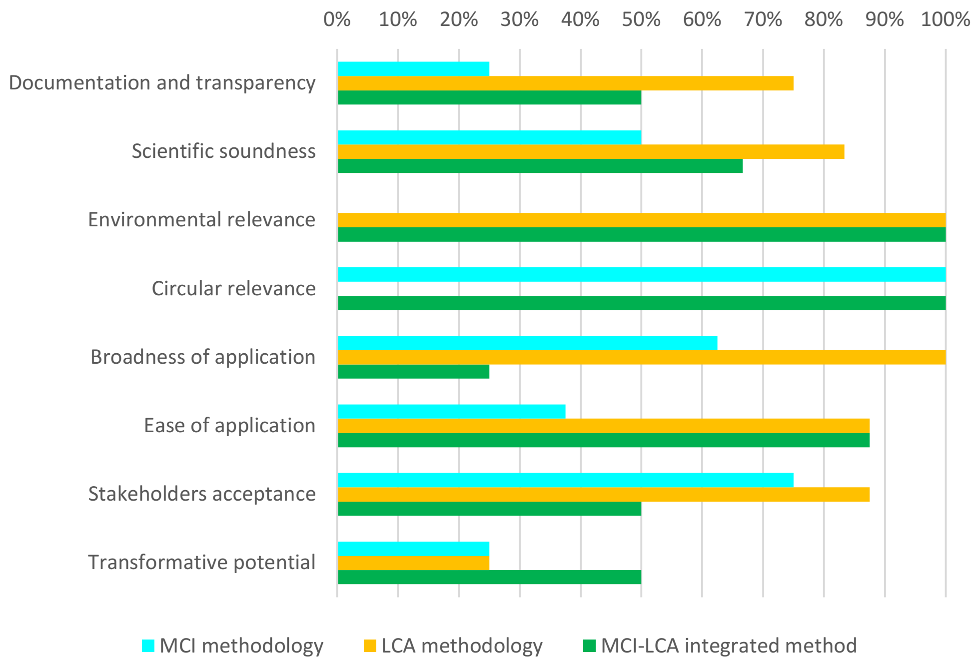


Figure 4.2: Evaluation of the progress achieved by the thesis compared to the MCI and LCA methodologies according to the semi-quantitative evaluation scheme adapted from Reimann et al. (2010), Hauschild (2010), and Forin et al. (2018).

4.1.2 Limitations of the MCI-LCA integrated method

The results of this thesis and Section 4.1.1 highlighted the advantages of the MCI-LCA integrated method, which clarified the requirements to guarantee the conformity with available ISO standards and provided solutions to tackle application related challenges.

Remaining limitations of the method need to be discussed. These are categorized in the following into development-related limitations, which are partially resumed from the discussion section of the 3. publication and can be improved by further work within the same methodological scheme, and intrinsic limitations, that are linked to the scope of the method.

Development-related limitations

The most relevant development-related limitation is the presence of several assumptions that affect the results. First, the lifetime, the recycling rate, and the circular biological cycles assumptions affect the validity. The lifetime assumption to neglect the use phases of products is a direct approximation of their limited duration and length. The efficiency of the recycling process used for the portion of a product collected for recycling is assumed to be 49% for all case studies, as the municipal waste recycling rate for 2020 in the EU (EEA, 2022). This assumption allowed highlighting and comparing the material for recycling flows of each case study under the same recycling conditions. It was necessary because of the lack of data and since data collection for this purpose is a long and complex process due to the quantity of materials and elements (Rufí-Salís et al. 2021). In the modeling to determine MCI, flows about biological circular cycles are represented by sustained biological feedstock and product to composting flow. This research wanted to get the hint from the EMF by determining the sustained biological feedstock in the primary biological raw materials of organic products thanks to the contact points between the EMF methodology (2019) and the EU organic definition (EUR-LEX, 2018) about limiting the use of non-renewable resources and developing healthy soils. This principle is assumed to be true because it provides the starting point of a theoretical framework of reference to be validated with further case studies concerning circular biological cycles. The product to composting flow was assessed for both organic and non-organic products and set at the EU average percentage (11%) of municipal food waste composted in 2020 (Eurostat, 2022; EEA, 2020) to give concreteness to the process of natural systems regeneration of biological cycles.

Secondly, all MCI results are highly dependent on how the system boundary is defined. Including waste generation in the extraction process would for instance significantly increase the material input and waste creation in all the scenarios. In MCI, this would affect the ratio of linearly flowing resources and generate lower circularity results. Furthermore, the system boundary contributes to affect the presence of rebound effects. These concern the environmental impacts related to the application of CE principles, which, although negative with respect to a single product system, to a larger scale involving product systems in close proximity are positive (Zink and Geyer, 2017). Therefore, for that reason and since MCI resulted in substantially more positive results than life cycle impact categories, a system expansion would potentially increase the validity when comparing to environmental impact indictors. Though, the poor availability of accurate data on product use and user behavior makes it difficult to perform more extensive evaluation in the current circular-environmental assessments (Harris et al., 2021). Despite the unpredictable nature of highly complex market systems is strictly related to the presence of rebound effects, wide-ranging efforts among circular and environmental experts are desirable to produce products and materials that truly are substitutes for primary production alternatives, brake/reduce aggregate demand for goods, and draw consumers away from primary production (Zink and Geyer, 2017).

Thirdly, the results are also affected by how the linear scenario is defined. According to EMF (2019), the MCI result by definition is 0% in the linear scenario and 100% in the circular scenario. A theoretically 100% circular scenario is free of material input and output but could still require energy to provide a defined FU. Such a scenario would generate conflicting results between MCI and LCA, as MCI would result in 100% circularity, while the system would not be free of environmental impact according to LCA. Considering this, in the 3. publication results, secondary raw materials were counted together with renewable primary energy resources – used as raw material (by converting their flows from MJ to kg) as circular flows in the MCI calculation, while energy carrier resources remained excluded. Using this interpretation, environmental impact is not directly proportional to circularity variation. For instance, by doubling a product lifetime, the circularity value of MCI is 50% as the required amount of materials is halved. LCA results are affected differently by this assumption, as other aspects than material use affect life cycle impact categories, and it cannot be expected to achieve complete correspondence between MCI results and specific impact categories.

Lastly, a further limitation of the method is the insufficient amount of case studies that tested the viability of the scenarios proposed in the 3. publication. The paper presents several assessments on which decisions on the most appropriate circular-environmental strategy can be based on. However, the availability of a wider pool of products will be necessary to test the viability of the outlined scenarios and develop a set of evidence-based recommendations for the circular-environmental assessment of products. One of the method's own added values, i.e., the need of two homologous products belonging to the same product category to be compered in the proposed circular-environmental assessment panel, might represent a limitation. This aspect could be partially offset by the inclusion of biological circular cycles according to the EMF (2019) in the circularity assessment of the proposed integrated model since no agri-food studies are present in the literature in which circularity assessments comprise both technical and biological cycles.

Intrinsic limitations

The literature analysis carried out in the 1. publication led to MCI as the most cited tool for circular evaluations. In particular, the MCI was the most popular among 55 sets of circularity indicators developed at different levels of the CE loops (maintain, reuse, remanufacture, recycle), the performance (intrinsic, impacts), the perspective of circularity (actual, potential) they consider, their degree of transversality (generic, sector-specific), or the CE implementation (micro, meso, macro). MCI belongs to the category of micro-level circular evaluation indicators which measure product performance including actions limited to consumers, products, and firms (Ghisellini et al., 2016; Kirchherr et al., 2017). A comprehensive CE approach is possible through an integrated vision of sustainability at macro, meso and micro-level (Prieto-Sandoval et al., 2018). Urban-industrial symbiosis, supply chains using end-of-life products and eco-industrial parks represent meso-level scale (Domenech et al., 2019, van Bueren et al., 2021), and could be the trait d'union between micro and macro level scales since the latter's environmental impacts are not quantified by universally recognized methods. At a meso-level, the influences are limited to the production side and include competitors and their interactions between external businesses, institutional players, and a broader set of contextual factors, such as market and user-level changes in technology and investments in science and culture, to gain economic and environmental benefits (Zhu et al., 2007). Applicative examples of this concept are the regional innovative networks (e.g., the Italian "Reti Innovative Regionali") that operate in innovative areas of any sector and can develop a set of initiatives and projects relevant for the regional economy, not necessarily limited to a specific production area but open to multi-sectoriality (Interreg, 2023). The synergies at the meso-level may influence the implementation of innovative approaches thanks to the leadership skills (Truong and Barraket, 2018) and executive choices (Pasricha et al., 2018) of the single micro-level parties involved. Therefore, though recent initiatives in meso and macro scales emerged in literature (Pauer et al., 2019; Spierling et al., 2019) which also included the LCA tool for their environmental assessments (Schulz et al., 2020; Schwarz et al., 2021), further research and development efforts are necessary to promote the monitoring of the global and national changes occurring in the environments, and the consequent policy-level responses by governments towards sustainable growth.

5 Conclusions and Outlook

CE and BE as a means of reducing environmental impact were found to be central to international policies, and reliable and applicable science-based methods and tools are necessary to measure the circularity performances of products and to assess their relationship with the environmental impacts associated with them. The measurement of circularity through specific indicators is an essential requirement for policy implementation processes and the consequent achievement of concrete actions and measurable results in the transition to the CE. However, though in recent years there has been increasing theorization about the possibility of integration/combination between environmental assessment and circularity assessment, the latter lead to a non-univocal consensus and to evaluations not yet consolidated, which suggests a potential need for further investigation in alternative models. Also, literature studies showed that there are no case studies applied to current integration models to assess whether circularity (both in terms of biological and technical cycles according to the EMF methodology) means reducing environmental impacts. Based on the most recognized and effective circular and environmental measurement tools, this thesis aimed at proposing an effective product circularity-environmental assessment tool which indicates whether applying circular principles can improve or worsen the environmental impacts of products.

To facilitate the choice of the most appropriate assessment methods for this purpose, several systematic literature reviews were performed. Firstly, a quali-quantitative assessment of several indicators to measure circular and environmental performances of products was completed (1. publication) whose results led to the MCI by the EMF as the most cited circular economy and bioeconomy indicator (i.e., 51 CE papers and 23 circular BE papers in the period 2010-2020), and LCA as the most suitable environmental impacts assessment tool within bioeconomy (i.e., the 83% on average of the BE environmental impact papers in the period 2010-2020). Secondly, several literature integration/combination patterns between circularity and environmental assessments were detected (2. publication): the separate conduction in which there are neither methodology nor results integrations, and the single tool separate conduction in which the environmental and circular assessments are conducted separately while the independent results are combined each other and joint in a single tool. Both models led to a non-univocal consensus and to evaluations not yet consolidated.

To address the research needs, several literature insights were outlined which suggested the possibility for MCI to provide extra information within a more extensive LCA evaluation in a framework where either the methodologies or the results were integrated. The EMF suggestion to use complementary indicators (calculated using the LCA methodology) together with the MCI through a Cartesian graph was received to obtain an in-depth analysis of the circular and environmental performance of the products. As a result, a MCI-LCA methodological integration model was proposed in which compared case studies were selected in the agri-food sector (since their products encompassed both biological and technical materials) to test and analyze the model (3. publication). As a result, an innovative circular and environmental assessment panel of coupled products belonging to the same product category was implemented. Specifically, five scenarios were detected in which the relationship between circularity and the relative environmental impacts varied according to the trend line slope linking the product analyzed to another comparable product. Scenarios no. 4 and 5 seemed to be the most preferred, and the fact that the scenario no. 4 (in which circularity increases significantly while environmental impact decreases gradually) resulted as the most detected encourages the implementation of even more circular-environmental practices. Compared to studies in the current literature, the added value of the application of the MCI-LCA integrated model is to allow for a comprehensive and holistic assessment through an innovative circular (both in terms of biological and technical cycles) and environmental assessment panel of coupled products (and the relative scenarios) belonging to the same product category.

Evaluated against specific criteria partly inspired and adapted from previous frameworks developed for evaluating impact assessment methods, the MCI-LCA integrated method developed in this thesis scored halfway between the MCI and LCA methodologies in the documentation and scientific soundness criteria through a detailed guidance that underwent a peer review process (3. publication). The broadness of application and the stakeholders acceptance were the criteria in which the integrated method performed worse than the single methodologies due to the exclusion of a life cycle phase, the presence of sector- and country-specific case studies, and the exclusion of NGOs/consumer organizations and public sectors from the integrated method’s application. The same performance as the LCA methodology was achieved in the environmental relevance and ease of application thanks to their common methodological backgrounds (which is the same reason for the equal circular performances of the developed method and MCI methodology), and the availability of data and software tools. A significant impact of the thesis is related to the linkage of the circular-environmental framework to suitable mitigation measures. Additional applications of the suggested pathways will provide the necessary empirical evidence to try to bridge the gap of standardized regulations on CE measurement framework, which has led to the current nonuniform indicator approaches.

The application of the MCI-LCA integrated method is affected by current challenges resulting from the presence of several assumptions that affect the results. First, the lifetime, the recycling rate, and the circular biological cycles assumptions affect the validity. Secondly, all MCI results are highly dependent on how the system boundary is defined, and the presence of rebound effects. Thirdly, the results are also affected by the definition of the linear scenario. A further limitation of the method is the insufficient amount of case studies that tested the viability of the scenarios proposed in the 3. publication. Intrinsic limitations of the MCI-LCA integrated method are the MCI belonging to the category of micro-level circular evaluation indicators which include actions limited to consumers, products and firms without considering the macro and meso levels. Integrating CE principles at macro, meso and micro-level is necessary not to have a limited vision so that to achieve sustainability through a comprehensive CE approach.

As a general outcome, applying the principles of CE did not always mean reducing the environmental impact, as it depended on the type of impact category and product. More compared case studies are required to be applied to the proposed integrated model for several reasons. Firstly, to strengthen the assumption of equivalence between sustained biological feedstock and primary biological raw materials of organic products. Secondly, to determine if eventual adjustments to the weighing system of technical and biological cycles are required. Ultimately, for the detected circular-environmental scenarios to be considered as general or sector guidelines for the integrated circular-environmental assessment of products and try to bridge the gap of standardized regulations on CE measurement framework, which has led to the current nonuniform indicator approaches.

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Glossary

Biological cycles

In circular economy, bio-based materials are used, consumed, and cycled in ways that regenerate natural systems and can be transformed using treatment types that generate cascades of value. (EMF, 2019)

Biological feedstock

The fraction of a product from Sustained Production. (EMF, 2019)

Characterization

Mandatory element of life cycle impact assessment. It describes the relationship between life cycle inventory results and impact category indicator reflecting the underlying environmental mechanism. (ISO, 2006a; ISO, 2006b)

Circular economy

A circular economy is a global economic model that decouples economic growth and development from the consumption of finite resources. (EMF, 2019)

Composting

For Biological Cycles, the act of converting the material into biologically accessible and otherwise uncontaminated nutrients. (EMF, 2019)

Feedstock

Feedstock is anything used to produce a new product. This in particular includes raw materials (from either virgin, bio-based, or recycled sources) but can also include components from old products reused in a new product. (EMF, 2019)

Impact category

Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned. (ISO, 2006a; ISO, 2006b)

Life cycle assessment (LCA)

Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. (ISO, 2006a; ISO, 2006b)

Linear economy

A linear economy consists of ‘take, make, dispose’ industrial processes and associated lifestyles resulting in a depletion of finite reserves. Virgin materials are used to create products that end up in landfills or incinerators. (EMF, 2019)

Material Circularity Indicator (MCI)

The main indicator developed in this methodology. It assigns a score between 0 and 1 to a product assessing how linear or restorative the flow of the materials for the product. (EMF, 2019)

Organic production

Overall system of farm management and food production that includes best environmental and climate action practices, a high level of biodiversity, and the preservation of natural resources. (EUR-LEX, 2018)

Product

Any goods or service. (ISO, 2006a; ISO, 2006b)

Raw material

Primary or secondary material that is used to produce a product. (ISO, 2006a; ISO, 2006b)

Recycling

Recycling is the process of recovering materials to feed back into the process as crude feedstock. Recycling excludes energy recovery. (EMF, 2019)

Sustained Production

In biological cycles, the extraction of natural materials at volumes and employing practices which aim to maximise the regeneration of natural systems in the indigenous ecosystems. (EMF, 2019)

System boundary

Set of criteria specifying which unit processes are part of a product system. (ISO, 2006a; ISO, 2006b)

Technical cycles

In technical cycles, products, components and materials are restored into the market at the highest possible quality and for as long as possible, through repair and maintenance, reuse, refurbishment, remanufacture, and ultimately recycling. (EMF, 2019)

Virgin feedstock

Material that is not from reuse, recycling or biological materials from Sustained Production. (EMF, 2019)

Waste

Substances or objects which the holder intends or is required to dispose of. (ISO, 2006a; ISO, 2006b)

List of figures