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EDITORIAL

Life cycle–based assessment methods for circular economy strategies in the agri-food sector

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1 Introduction

In recent years, the need for a transition from an economy based on a linear pattern (take-make-waste) to a circular economy (CE) model has become increasingly clear, in order to maintain the value of goods at every stage of their life cycle (Stahel 2016). In this regard, the interest in CE has escalated in the public and business agendas (Korhonen et al. 2018), and CE has gained increasing acceptance by governments, companies, and institutions due to its effective contribution to optimizing resource use and reducing environmental burdens (Bastianoni et al. 2023). In addition, according to Schroeder et al. (2019), CE practices may allow for the achievement of Sustainable Development Goals (SDGs), thus providing environmental, economic, and social benefits.

Among the international scientific literature, different studies have so far proposed and evaluated the implementation of CE strategies at various levels (macro, meso, and micro), focusing on products, companies, and networks between industries, cities, and nations (Ghisellini et al. 2016). Despite this, the measurement of CE-related impacts and the necessity of developing and applying dedicated CE indicators, or adapting existing tools and methods, as well as the evaluation of sustainability implications, are still contested issues (Elia et al. 2017; Sassanelli et al. 2019; Blum et al. 2020).

Several scholars pointed out the importance of analyzing CE following a life cycle perspective, thus considering Life Cycle Thinking (LCT) as a suitable approach for assessing the environmental, economic, and social implications of CE implemented in various sectors (e.g., Mondello et al. 2024; Roos Lindgreen et al. 2020; Moraga et al. 2019). Indeed, Life Cycle Assessment (LCA) and related methods may help in the achievement of more consistent CE strategies (Peña et al. 2021), as well as be integrated with dedicated CE indicators to obtain a more comprehensive assessment, thus considering the intrinsic characteristics of both circularity and sustainability (Samani 2023; Haupt and Zschokke 2017; Niero and Kalbar 2019; Rigamonti and Mancini 2021).

Among the various production sectors involved in the transition toward CE, agri-food is considered one of the most challenging in terms of achieving and implementing CE strategies (Muscio and Sisto 2020), but also in terms of identifying the pathways for generating and optimizing value (Poponi et al. 2022). Indeed, the agri-food sector is responsible for an unsustainable use of resources and production of waste, which results in environmental, economic, and social impacts. For instance, it contributed about 31% to the global anthropogenic greenhouse gasses (GHG) emission, causing about 16 billion tonnes of carbon dioxide equivalent (CO_{2eq}), in 2020 (FAO 2022). In addition, 14% of the food globally produced is lost during agricultural processes, causing an estimated economic loss equal to USD400 billion, while 17% is wasted by retailers and consumers (Food and Agriculture Organization of the United Nations 2024). Agri-food systems also represent a complex set of different economic activities (including primary, secondary, and tertiary sectors). On the one hand, such activities are based on

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natural processes (e.g., agricultural practices) and therefore belong to the biological cycle. On the other hand, they are characterized by industrial processes, which strongly depend on the biological features of the processed materials, thus being part of both biological and technical cycles (Gulisano et al. 2018). Thus, CE strategies and related circular business models in the agri-food sector need to be implemented by simultaneously involving both biological and technical components (Stillitano et al. 2021).

Despite its challenges, the agri-food sector may also represent an important opportunity for the implementation of the CE concept. For example, proposing suitable actions for food waste treatment (e.g., anaerobic digestion or bioconversion by insects) would allow both the improvement of the environmental, economic, and social performance of the entire agri-food sector and the opportunity of implementing CE strategies through the valorization of the embodied value of the food wasted (Mondello et al. 2017; Salomone et al. 2017). The added value connected to the optimization and reduction of the resources used in the agricultural and production processes as well as to their related waste should be evaluated not only in terms of sustainability improvement but also focusing on CE strategies. In addition, the implementation of CE strategies in the agri-food system involves not only agricultural products or food but also food packaging, which has become more and more common and complex due to the eating habits and food behavior of modern society. Recycling technologies aim to provide a solution for packaging management after the use phase but also during the production phase of the packaging itself, through the implementation of CE strategies that take into account the chemical safety of recycled materials used for food packaging (Geueke et al. 2018; Jang et al. 2020). Besides, according to Zambujal-Oliveira and Fernandes (2024), the use of sustainable packaging is fundamental in the agri-food sector in order to achieve circular practices by reducing food waste production and the related environmental impacts.

Despite the importance of implementing CE strategies in the agri-food sector, there is still the need to define how their sustainability and related potential impacts or benefits can be assessed. In this regard, Peña et al. (2021) pointed out that it is necessary to fully understand how to integrate LCT approaches and CE indicators to assess the sustainability performance of CE strategies.

2 Scope of this special issue

Within the aim of *The International Journal of Life Cycle Assessment*, the scope of this special issue (SI) was to collect high-quality original papers and review papers focused on the methodological and practical assessment of CE strategies in the agri-food and related sectors (packaging and energy) using LCT-related methods (e.g., LCA, Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA)). The SI wished to promote, evaluate, and understand the role of LCT methods in supporting and measuring the sustainability of CE strategies as well as their integration with dedicated indicators, by focusing on one (or more) of the three areas of interest here presented:

1. Agri-food sector and related activities (e.g., agricultural processes, food production, food storage and transportation, food consumption and services, food waste production and treatment), assessing resource use optimization and/or waste reduction or treatment in a CE perspective
2. Food packaging and related processes (e.g., raw material extraction, industrial production, reuse activities, post-consumer waste management) in relation to the implementation of different CE strategies
3. Energy related to the agri-food sector, focusing, for example, on CE strategies based on the improvement of energy systems (e.g., energy sources for agricultural machinery, food transformation, food storage and refrigeration) or the assessment of the embodied energy of food waste products.

The SI attracted considerable interest and attention from the scientific community and a total of 10 original and review papers were published.

3 Overview of the papers included in this special issue

The 10 papers included in this SI (Table 1) are focused on methodological development, case study analysis, and literature reviews regarding the use of LCT methods for assessing CE strategies in the agri-food and related sectors, also including the integration of such methods with CE indicators.

Among the studies aimed at proposing methodologies and frameworks, Gallo et al. (2023) proposed a methodology that correlates circularity and environmental impacts based on the Material Circularity Indicator (MCI) (EMF and Granta 2015) and LCA, respectively. The suggested approach was applied to six case studies in the agri-food sectors (i.e., jam, flour, pasta, olive oil, mozzarella cheese, chicken breast) comparing two versions of the same product, an organic one (originating from organic production) and a non-organic one (originating from conventional production). Results showed that an increased circularity did not always lead to a reduction of environmental impact, as it depends on the type of impact category and product investigated. The added value of the application of the MCI-LCA integrated model is to allow for a comprehensive and holistic

Table 1 The 10 papers included in this special issue

	Author	Title	Type of study
1	Gallo et al. (2023)	Integration of a circular economy metric with life cycle assessment: methodological proposal of compared agri-food products	Methodological
2	Møller et al. (2023)	Circularity indicators and added value to traditional LCA impact categories: example of pig production	Methodological
3	Ruggieri et al. (2022)	Life cycle-based dashboard for circular agri-food sector	Methodological
4	Kerdlap et al. (2022)	UM3-LCE3-ISN: a methodology for multi-level life cycle environmental and economic evaluation of industrial symbiosis networks	Methodological
5	Notarnicola et al. (2022)	Life cycle inventory data for the Italian agri-food sector: background, sources and methodological aspects	Literature review
6	Silvestri et al. (2022)	Toward a framework for selecting indicators of measuring sustainability and circular economy in the agri-food sector: a systematic literature review	Literature review
7	Sica et al. (2022)	The role of digital technologies for the LCA empowerment towards circular economy goals: a scenario analysis for the agri-food system	Literature review
8	Ahmad et al. (2023)	Environmental impacts and improvement implications for industrial meatballs manufacturing: scenario in a developing country	Case study
9	Vinci et al. (2022)	Environmental life cycle assessment of rice production in northern Italy: a case study from Vercelli	Case study
10	Ncube et al. (2022)	Circular economy paths in the olive oil industry: a Life Cycle Assessment look into environmental performance and benefits	Case study

assessment through an innovative circular assessment (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. The study proposed by Møller et al. (2023) evaluated the methodological choices related to the use of both CE indicators and the LCA methods by assessing circular strategies for livestock systems. The results from the study highlighted that, on the one hand, CE indicators and impact categories in LCA can be integrated and complementary or adopted separately; on the other, the selection of CE indicators strongly depends on what is defined in the goal and scope definition phase. Instead, Ruggieri et al. (2022) aimed to define a life cycle–based dashboard to systematize and test cross-sectional life cycle–based indicators to evaluate their applicability to the circular agri-food sector. Indicators were classified according to (i) spatial dimensions of CE (macro, meso, and micro), (ii) areas of sustainability (economic, social, and environmental), and (iii) scope (emission, water, chemical use, energy input, waste management, impact, human rights), within which the indicators are applied. Indicators were tested through a multiple compared analysis at the national (Italian) and regional level, including a company case study. The study's results highlighted the ability of cross-sectional indicators to provide a comprehensive overview of the circularity of the agri-food sector concerning each level of observation. Lastly, Kerdlap et al. (2022) developed a methodology for multi-level life cycle environmental and economic evaluation of industrial symbiosis networks and tested it in a case study of a fictitious network of five urban agri-food production companies (i.e., a soil farm, a hydroponics farm, a brewery, an egg farm, and a fish farm) that participate in waste-to-resource exchanges among each other. Such methodology, named UM^3-LCE^3-ISN, is able to construct a single matrix-based model that represents an industrial symbiosis network and can produce LCA and LCC results at the network, entity, and flow levels. It represents an advancement in the development of tools and software that aim to provide different stakeholders in industrial symbiosis networks with the ability to operate on a single platform when measuring the environmental and economic performance of different options to ultimately support the decision-making process in a CE context.

Regarding the review studies, Notarnicola et al. (2022) investigated the consistency, coherence and representativeness of the current Life Cycle Inventory (LCI) databases to regional/site specificity scenarios, focusing on the four Italian supply chains, i.e., olive oil, wine, wheat and pasta, and citrus fruits. The authors pointed out the lack of relevant datasets related to these products for the Italian background as well as the need to develop a new representative database, including also data related to CE strategies. Silvestri et al. (2022) performed a systematic literature review with the aim of providing a comprehensive framework of indicators for measuring sustainability and circular economy in the agri-food sector. Three main clusters of studies were identified: (i) "assessment-LCA" (i.e., studies adopting the LCA method to analyze the environmental dimension of sustainability), (ii) "best practice" (i.e., studies aiming to define guidelines for the agri-food system to achieve global sustainability), and (iii) "decision making" (i.e., studies that aim to support agricultural producers and policymakers in the process of transitioning toward sustainability). Results showed that there is an increasing trend in the use of LCA, LCC, and S-LCA in the assessment of sustainability and CE strategies in the agri-food sector. Sica et al. (2022) through a literature review and an in-depth interview submitted to senior researchers provided a scenario analysis related to the benefits and barriers of using digital technologies for LCA (namely, empowered LCA) to guide CE transition towards the agri-food sector. Through the identification and evaluation of different constructs, the authors highlighted the importance of digital technologies to have a more reliable LCA when CE strategies are implemented in agri-food systems.

Focusing on the case studies, Ahmad et al. (2023) evaluated the environmental impacts caused by beef meatball production in Malaysia focusing on farming activities, meat manufacturing, and packaging. CE practices were proposed in order to improve the environmental performance related to the analyzed system. The results pointed out the usefulness of combining the LCA method with CE principles to identify environmentally friendly oriented strategies. Furthermore, Vinci et al. (2022) assessed the potential environmental impacts of rice production in Northern Italy, identifying the most critical hotspots of agricultural activities. The results highlighted that the highest environmental load come from direct emissions and energy consumption of irrigation practices. In this regard, the authors compared different water management systems and identified the intermittent flooding of the paddy field as the preferable technique to reduce impacts. In addition, different circular strategies focused on agro-waste use were proposed, highlighting the fundamental role of CE practice in mitigating emissions in the agri-food sector. Lastly, in the study of Ncube et al. (2022), the LCA method was applied to investigate the potential environmental impacts of linear and circular extra virgin olive oil supply chains. Specifically focusing on the assessment of CE strategies, the authors evaluated the environmental performance related to by-products and waste (e.g., pomace, pruning, or exhausted cooking oil) by applying the system expansion with a substitution approach. Results underscored relevant environmental benefits related to the adoption of circular practices in olive oil.

4 Main remarks from the special issue

This SI was proposed to collect relevant original and review studies in order to investigate data and information on methodological and practical aspects regarding the usefulness of LCT-related methods for assessing CE practices in agri-food and related sectors (i.e., packaging and energy). This SI also provided important methodological aspects related to the added value and peculiarities of such methods when combined with dedicated CE indicators. A total of 10 papers were collected including methodological advancement, literature review, and case study analysis. In particular, various frameworks were investigated among the studies focusing on the assessment of the sustainability performance of the agri-food sector from a CE point of view, through the use of life cycle–based indicators. Furthermore, the literature review studies highlighted the need for dedicated LCI data as well as they provided a set of available indicators for assessing both sustainability and CE from a life cycle perspective. On the other hand, case studies were focused on livestock and agricultural production by analyzing potential strategies for waste and by-product valorization through the application of LCT methods or by their integration with CE indicators. LCA emerged as the most adopted method, pointing out that the scientific community is mostly oriented on analyzing the environmental performance of circular strategies in the agri-food sector, rather than the economic and social impacts. Indeed, only one study (Kerdlap et al. 2022) investigated the use of the LCC method in combination with LCA, while no studies were focused on the S-LCA one, except for the paper proposed by Silvestri et al. (2022) in which life cycle–based indicators related to the assessment of the three pillars of sustainability were identified through a literature review. This underscores the need for a more comprehensive assessment of circular strategies considering all the dimensions of sustainability, with specific regard to the social one, which is currently the least investigated. In addition, among the collected papers, no studies adopted LCT methods to be applied at the organizational level (i.e., Organizational LCA or Social Organizational LCA), highlighting that sustainability assessment of CE strategies in the agri-food sector is mainly performed focusing on products or processes, instead of the whole activities in which a company is involved. Lastly, no studies were specifically focused on packaging or energy as sectors directly involved in agri-food systems. Despite this, different papers (e.g., Møller et al. 2023; Ruggieri et al. 2022; Ncube et al. 2022) included, in the proposed frameworks and case study analyses, the assessment of circular strategies related to packaging (e.g., use of alternative materials) and energy sources (e.g., energy recovery or bioenergy production). This leaves a lot of room for further investigation of the interconnection between life cycle sustainability assessment and circularity assessment in the agri-food sector.

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