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A systematic and critical review of life cycle approaches to assess circular economy pathways in the agri-food sector

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ABSTRACT

This study provides a literature review of life cycle approaches used to assess circular economy (CE) pathways in the agri-food sector. The scope of this review is to understand how and how much the LC-based analysis is useful to evaluate if CE strategies are more sustainable than linear/traditional economic models in agri-food production systems. To carry out the systematic and critical literature review the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was employed. The literature search was performed employing scientific databases (Scopus and Web of Science). The results highlight that 52 case studies out of 84 (62% of the total) use stand-alone life cycle assessment (LCA) to evaluate the benefits/impacts of circular economy strategies. Only eight studies (9.5%) deal with the life cycle costing (LCC) approach combined with other analyses, while no paper deals with the social life cycle assessment (S-LCA) methodology. We argue that experts in life cycle methodologies must strive to adopt some key elements to ensure that the results obtained fit perfectly with the measurements of circularity and that these can even be largely based on a common basis.

Keywords: Systematic literature review; Circular economy; Life cycle methodologies; Agri-food sustainability.

1 Introduction

Circular economy (CE) is currently one of the most discussed concepts among researchers, politicians, and academics. Its main principle regards a more efficient use of resources and the decrease of wastes, stressing the necessity of reusing, recycling, and reducing to limit negative impacts on people and environment (Ellen MacArthur Foundation, 2013). CE is about the rethinking of the current models of production and consumption, and agri-food systems, which are responsible for the pressure on the living environment, must necessarily move toward transition pathways. Exploring the potential contribution of circular approaches to sustainable production in agri-food systems also means understanding how to pay more attention to the social, economic, and environmental aspects of sustainability. However, undertaking such different dimensions is methodologically challenging and calls into question the epistemological foundations of sustainability science and circular economy. One of the greatest concerns is around the combination of different assessment methods and merging their results in a suitable and believable way. Furthermore, evaluating CE strategies should require a systemic and synergistic approach by considering the agri-food supply chain as a whole, especially to not incur the risk of making effective only one stage nor only single portions, while neglecting the others (Niero and Hauschild, 2017; Colley et al. 2020). To satisfy these purposes, sustainability evaluation tools and, among them, the life cycle (LC) approaches are are particularly appreciated as a robust, science-based, and useful tool not only to measure, but also to validate CE assumptions, LC methodologies, i.e., the Life Cycle Assessment (LCA or eLCA), Life Cycle Costing (LCC), and the Social Life Cycle Assessment (sLCA), are obtaining a growing consensus in the appraisal of the environmental, economic and social impacts of different agricultural systems. In these terms, the use of a LC framework, able to capture all sustainability dimensions, can be adapted to evaluate circular economy strategies in an operational and comprehensive way.

This study aims at providing a systematic and critical literature review of the LC approaches used to assess circular economy pathways in the agri-food sector. The scope and approach of this review is to understand how and how much the LC-based analysis is useful to evaluate if CE strategies are more sustainable than linear/traditional economic models in agri-food production systems.

2 Materials and Methods

In order to conduct the systematic and critical literature review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol (Moher et al. 2009) was employed. PRISMA was used as a formal systematic review guideline for data collection providing a standard peer accepted methodology, to contribute to the quality assurance of the revision process and its replicability. The literature search was carried out in Scopus and Web of Science (WOS) databases, using specific keywords and Boolean operators. The search string applied to the databases was: (“circular economy”), (“life cycle assessment” OR "life cycle analysis" OR LCA), (“life cycle costing” OR LCC), (“social life cycle assessment” OR "S-LCA" OR SLCA OR "social-LCA), ("life cycle sustainability assessment" OR LCSA) combined with (“agr* OR food). The databases were consulted in October 2020 with no time restriction.

The research led to the identification of 596 articles. Duplicate papers were excluded, resulting in 464 documents, which have been subjected to a screening process. A first selection was made by excluding reviews and editorial material, and including only applicative indexed references and English language. A second screening was performed based on the content of abstracts, excluding discussion papers, or off-topic and studies that did not focus on the agri-food sector or life cycle approaches. In so doing, 122 articles were assessed for eligibility by reading the full-text in-depth. Studies not directly focused on the issue of measuring circularity quantitatively were discarded. Through the above-specified criteria application, a final portfolio of 84 papers was found and included in the qualitative synthesis. These articles were read in full and analyzed one by one for the purpose of this study.

To synthesize research evidence an evaluation matrix was set up, by classifying documents according to several integrated criteria (De Luca et al. 2017). All reviewed papers have been categorized by bibliometric information (authors, year of issue, title, journal); descriptive statistics that refers to the place where the case-study is applied, field of application (i.e., the area of human activity), the main product under study, circularity topics; and relevant data on circularity assessment methods and circularity indicators (Corona et al. 2019; Saidani et al. 2019). Finally, the last columns of the matrix are focused on the main features that qualify the life cycle approaches, e.g., functional unit, system boundary, database, LC impact assessment method, software, etc.). Once the matrix has been completed, the input data were compared and the results were qualitatively and quantitatively extracted to highlight significant information and relationships.

3 Research results

3.1 Descriptive analysis

The reviewed 84 papers showed that the interest on the application of LC approaches as circularity metrics in the agri-food sector rose from 2014 onward. Nevertheless, as mentioned by Vetroni Barros et al. (2020), the peak development of this theme has yet to be reached. Considering the place of case-study application, the five highest-ranked origins of the reviewed articles are Spain (22.6%), Italy (14.3), United Kingdom (UK) (7.1%), China (6%), and Ireland (4.8%). The interest in using LC tools to analyze CE strategy seems to be growing in Brazil and Sweden with 3 publications each. According to the type of contribution, 83 articles out of 84 were published in scientific peer-reviewed journals and only one in proceedings of scientific international conferences. The highest-ranked journals were Journal of Cleaner Production (21), Science of the Total Environment (10), Resources, Conservation and Recycling (8), Waste Management (5), and Sustainability (4), with 57.1% of documents considered.

Concerning the main argument covered in the studies analyzed, the waste and/or biomass fields of application were the most addressed by the published articles accounting for 55% of the total. Here, “Wastes” refers to the use and recycling of household wastes (e.g., de Sadeleer et al. 2020), wastewater (e.g., Chen et al. 2020b), agricultural wastes (e.g., Cortès et al. 2020, Qin et al. 2018), food waste (e.g., Edwards et al. 2017), and organic waste (e.g., Cobo et al. 2020, Monsivais-Alonso et al. 2020), including recovery of nutrients (e.g., Cobo et al. 2018a), organic compounds, and energy (e.g., Laso et al. 2018a). In the field named “Biomass”, several kinds of goods for energetic purposes, bio-energy (e.g., Buonocore et al. 2019), biogas (e.g., Lansche et al. 2020), biofuel (e.g., Eggemann et al. 2020) were included. Around 15% of the studies were included in the “Manufacturing” field, which includes product production from raw materials (renewable or not). The “Agriculture” field, account-ing for 11% of the total, enclosed production of fruits and vegetables (e.g., Arunrat et al. 2021) for fresh consumption or industrial transformation (e.g., Oldfield et al. 2017) (raw materials, food, and no food). Considering the reference product analyzed in the case studies, “Food waste” is the most repre-sented product category (11%). Other main reference products identified in this review included sev-eral agro-industrial products, such as tomato (e.g., Corcelli et al. 2019, Rufí-Salís et al. 2020b), an-chovy (e.g., Laso et al. 2018b), maize (e.g., Gaglio et al. 2019), pig (Noya et al. 2017), olive (e.g., Moreno et al. 2020), dairy (e.g., Ghisellini et al. 2014, Stanchev et al. 2020, Wohner et al. 2019), corn (e.g., Cobo et al. 2018a) and rice (e.g., Arunrat et al. 2021, Belaud et al. 2019), as well as poultry (e.g., Beausang et al. 2020), coffee (Schmidt Rivera et al. 2020). The most common circularity topics that emerged in this study’s final portfolio were “Waste valorization”, accounting for 32% of the total (e.g, Chaudron et al. 2019, Martin et al. 2019, Roffeis et al. 2017; 2020) and “Energy recovery”, with about 29% of the final portfolio. (e.g., Wolsey et al. 2018, Slorach et al. 2019). To follow, the “Recycle” topic was observed in 15% of the total documents (e.g., Boesen et al., 2019).

3.2 Circularity assessment frameworks

This review found 52 case studies out of 84 (62% of the total) using stand-alone LCA. LCA is consid-ered by all authors as the most suitable methodology to assess products, services, technologies in a CE perspective. On the contrary, only 8 studies (9.5%) deal with the LCC methodology combined with other analyses, while no paper deals with the sLCA methodology.

Most of the reviewed stand-alone LCA is performed following several impact evaluation methods that include multiple indicators representing up to 16 different impact categories. In particular, the most common LCA indicators were Global Warming Potential (or Climate Change or Carbon Footprint) ap-plied in 58 papers (67% of the total), Eutrophication (for marine, freshwater, and terrestrial ecosys-tems) in 45 papers (55%), Human toxicity in 28 papers (35%), and Ecotoxicity in 25 papers (30%). The most applied method was Recipe, accounting for 38.5% of the total papers (e.g., Beausang et al., 2020; Buonocore et al., 2019; Corcelli et al., 2019; Cortés et al., 2020). The other two most applied methods in the literature review were CML, accounting for 21.2% (e.g., Krishnan et al., 2020) and ILCD with 17.3% (e.g. Martinez et al. 2020; Tedesco et al., 2019). Considering the importance of en-ergy consumption in the agricultural systems, some authors also included in their analyses the cumula-tive energy demand (CED), an impact indicator that expresses the energy consumption throughout the life cycle of a product or a service (Gaglio et al. 2019, Lansche et al. 2020, Rufí-Salís et al. 2020a, Strazza et al. 2015). Others focused on the primary energy demand (PED), which represents an appro-priate indicator for illustrating the interactions of the food-energy nexus (Oldfield et al., 2017; Piezer et al., 2019; Schmidt Rivera et al., 2020). Few studies used water footprint (WF) indicator (Krishnan et al., 2020), known worldwide for the assessment of environmental performance.

As above-mentioned, few studies adopted LCC methodology as a tool for measuring CE strategies from an economic point of view. A conventional (C-LCC) and societal (S-LCC) life cycle costing paired with LCA were performed by Albizzati et al. (2021) and Blanc et al. (2019). By combining the LCC model and externalities in the CE, Albuquerque et al. (2019) analyzed the benefits of using alu-minum packaging in the food sector. As discussed by the researchers, it is necessary to adopt the LCC approach as a useful economic model to guide the solutions for sustainable manufacturing and the CE vision.

In many case studies reviewed, CE strategies were assessed through LCA combined with other “life cycle-type” approaches, i.e. methods not directly ascribed to typical LC framework (i.e, LCA, LCC, and sLCA), but that approached the evaluation process in a life cycle perspective. Among the other methodological approaches most applied, there were Material Flow Analysis (MFA) (de Sadeleer et al., 2020; Cobo et al. 2018a and 2018b; Stanchev et al., 2020), Input-output (IO) analysis (Chen et al., 2020a), and Carbon Footprint (Arunrat et al. 2021) implemented coherently with principles and meth-odological steps of an LC-based approach.

3.3 Circularity assessment indicators

The research results found only 8 articles that deal with the CE assessment through specific indicators. In this review we refer to the classification of CE assessment indicators proposed by Corona et al. (2019), who identify indicators that measure the circularity degree of a system, based on a mere mate-rial recirculation and addressed to resource efficiency, and indicators that assess the effects (burden or value) of circularity. Here, by LC-based indicators, we refer to the life cycle impact categories indica-tors retrieved from LCA, the LCC indicators when utilized for evaluating CE strategies, and stand-alone indicators based on life cycle approaches. Some CE indicators examined in this review were developed to assess the circular degree of a system. For instance, Cobo et al. (2018a) applied the circularity indicators of carbon (CIC), nitrogen (CIN), and phosphorus (CIP) to a circular integrated waste management system that handles organic waste (OW) generated in Spain, while Hoehn et al. (2019) used the energy return on investment (EROI) ratio, and a CE perspective, to develop an energy return on investment - circular economy index (EROIce) to quantify the amount of nutritional energy recovered from the food loss in the Spanish food supply chain.

Advancements in the assessment of CE strategies at the product level have been suggested by Niero and Kalbar (2019), who coupled two sets of indicators via multi-criteria decision analysis, i.e., mate-rial circularity based-indicators - namely, material re-utilization score (MRS) and material circularity indicator (MCI) - and a selection of life cycle based-indicators (climate change, abiotic resource deple-tion, acidification, particulate matter, and water consumption). The MRS is the metric used to quantify material re-utilization developed by Cradle to Cradle Products Innovation Institute (C2C), while the MCI is the main index developed by the Ellen MacArthur Foundation (EMF) and Granta to measure how well a product performs in the CE context. The authors suggest exploring the application of the multicriterial analyses of LC-based indicators (including the socio-economic dimension) to address CE trade-offs and rebound effects.

In a complementary manner, Schmidt Rivera et al. (2019) proposed a set of indicators integrating tech-no-environmental and CE criteria to guide the design and development of new food packaging solu-tions within the new plastics economy. Stanchev et al. (2020) also developed an approach for measuring the material and environmental circularity performance of the anaerobic treatment of dairy processing effluents. Material CE performance was assessed by the “Material circularity performance” indicator (MCPI), suggested by Agudelo-Vera et al. (2012), which enables to evaluate to what extent the de-mand of resource or energy flows reduced when the circularity loops are closed. Laso et al. (2018a) suggested a method to assess the eco-efficiency of canned anchovy products with the eco-efficiency index (EEI), by combining LCA (global warming potential, acidification potential, eutrophication po-tential, and ReCIPE single score) and LCC (value-added) indicators.

Lokesh et al. (2020) proposed a new set of hybridized sustainability indicators, drawn from the princi-ples of green chemistry and resource (material and energy) circularity, to evaluate the environmental performance of bio-based products, bio-based packaging films, and mulch films in comparison with their commercial counterparts. Finally, Santagata et al. (2020) used emergy-based circular economy indicators (no life cycle-based) to assess the sustainability of the urban eco-system. These indicators were developed by using Emergy accounting (EMA), which accounts for different categories of sup-porting contribution to the systems, including renewable and non-renewable energy and material re-sources, information and knowhow, and finally labor and services.

4 Conclusions

This research operated a systematic literature review with the aim to provide a picture of the state-of-the-art of life cycle applications in the assessment of circularity of processes and products.

The analysis of the literature highlights that the studies do not aim at a true "circular strategy" since circularity is not really measured in most of them. Most articles use indicators relating to the use of material and energy resources but this is not enough to define the degree of circularity of a process or product, just as circularity alone cannot define sustainability. LCA can assess the environmental im-pacts of a process and, through an eco-design approach, allows for the implementation of strategies to reduce these impacts, including a reduction in the use of resources and by considering the bur-den-shifting phenomenon whereby a change in one stage of the life cycle influences another one (Sala et al., 2016). What attributional LCA cannot assess are rebound effects, a key element in sustainability assessments because it takes into account changes in production and consumption when the availabil-ity of a resource change (positively or negatively) (Font Vivanco et al., 2014).

For these reasons, the assessment of circularity must pass through a multi-component approach that takes into account not only circularity itself but also other characteristic elements. The analysis of the papers shows the opposite situation, where the assessment of impact factors becomes the main driver for measuring sustainability (eg. Arunrat et al., 2021), while circularity rather remains a goal to be achieved but hardly ever explicitly measured.

It should not be forgotten that talking about LCA is probably reductive since it should be part of a multi-objective framework (i.e. LCSA) aimed at analyzing the integrated sustainability of a process, product, system, or organization (De Luca et al., 2017). In this direction, as already discussed some studies have already explored the possibility of also using the LCC methodology in the assessment of circularity. While the main circularity indicators are essentially based on the increase in the utility of re-sources within an economic model, an approach that assesses the life cycle value flows of a prod-uct, process, system or organization is a fundamental complement to both circularity and sustainability assessment.

While the methodologies discussed so far mainly refer to environmental and/or economic metrics, the role that the large-scale economic model change will bring to the social level cannot be neglected. Among the reviewed papers, no one applies the sLCA or another specific methodology for social im-pacts assessment. Rather, some kind of social impacts are explicitly associated, in some few cases, with economic performances.

The methodological development in this field is constantly evolving. In particular, experts in life cycle methodologies must strive to adopt some key elements to ensure that the results obtained fit perfectly with the measurements of circularity and that these can even be largely based on a common basis.

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