Science of the Total Environment 903 (2023) 166611

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Synergies and gaps between circularity assessment and Life Cycle Assessment (LCA)

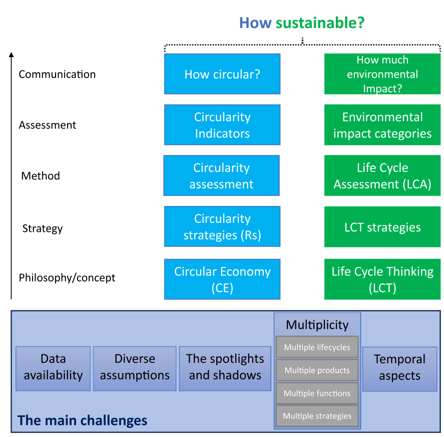
Pouya Samani

Netherlands Organization for Applied Scientific Research (TNO), Circularity and Sustainability Impact (CSI), Princetonlaan 6, 3584 CB Utrecht, the Netherlands

HIGHLIGHTS

- The synergies between circularity assessment and LCA are reviewed
- The gaps and challenges of both assessments are analyzed
- How to handle multiplicity in circularity assessment and LCA is explained
- The temporal aspects and its challenges in LCA are elaborated
- Possibilities for diversifying circularity assessment and LCA are discussed

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Life Cycle Assessment
Circularity assessment
Circularity indicators
Circular economy
Circularity strategies
Sustainability assessment

ABSTRACT

This article evaluates the synergies between circularity assessment and Life Cycle Assessment (LCA) by investigating their alignments, misalignments, and challenges in addressing sustainability. The analysis emphasizes the significance of a multi-level approach, positioning these methods at various levels, including philosophy, strategy, assessment, and communication. The findings demonstrate that both LCA and circularity assessment can serve as sustainability assessment methods for circularity strategies, despite existing gaps. However, neither approach can provide a complete picture of a system's environmental performance on its own. Data availability, diverse assumptions, spotlights and shadows (highlighted and neglected elements), multiple life cycles, products, functions, strategies, and as well as temporal aspects are identified as the main challenges in addressing sustainability. This article provides recommendations based on the lessons learned from each approach, suggesting the integration of their strengths and addressing challenges to achieve a comprehensive understanding of environmental sustainability and make informed decisions for a circular and sustainable future. These recommendations include using function-based models and the principles of prospective and dynamic LCAs for the development of future circularity assessments. Additionally, circularity assessment can be used to establish LCA models, aiding in identifying hotspots during the goal and scope definition, and determining allocation and weighting factors in both Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA).

E-mail address: pouya.samani@tno.nl.

https://doi.org/10.1016/j.scitotenv.2023.166611
Received 22 July 2023; Received in revised form 24 August 2023; Accepted 25 August 2023
Available online 26 August 2023

1. Introduction

1.1. Background

In the current times, the recognition of climate change as a threat and acknowledging sustainability as an essential goal has become exceedingly evident. The pursuit of sustainability can now be observed in the agendas of political leaders, business owners, and, perhaps most importantly, individuals. In the pursuit of this goal, various philosophies, concepts, frameworks, guidelines, methodologies, tools, and indicators are put forth as the 'unique' solution for driving the transition towards a more sustainable society. This encompasses a range of strategies, policies, and measurement techniques.

Life cycle thinking is all about going beyond the present moment and keeping in mind the past and the future, i.e., considering the entire life cycle. As Oscar Wilde once said, 'Every saint has a past, and every sinner has a future.' Similarly, a recyclable material may have generated a significant amount of emissions during the production phase or that product, which required a substantial amount of energy to be produced, may have a minimal impact on the environment during its end of life. Life cycle thinking has enlightened us about the importance of adopting a holistic perspective, which eventually led us to question the line itself and seek approaches like recycling to transform this line into a circle. Today, it is widely recognized that the circular economy extends beyond a single circle; it comprises numerous interconnected cycles of materials and products.

1.2. Circular economy

The circular economy has gained significant attention and endorsement from policymakers, especially in Europe (Bastianoni et al., 2023). Decision-makers have recognized the necessity of shifting from the current linear economy towards a more circular and sustainable model. Nonetheless, the latest circularity gap report indicates that the global economy is only 7.2 % circular, which is more concerning when compared to 9.1 % in 2018 and 8.6 % in 2020 (Circle Economy, 2023).

The political approaches to promote circular economy vary by region. For instance, in China, more top-down approaches are in practice, while in other parts of the world, such as the United States or the EU, bottom-up approaches are more prevalent (De Pascale et al., 2021). While some may view the circular economy as a recent approach, the concept of a 'closed economy' was first introduced by Kenneth Boulding in 1966 (Brandão et al., 2020). Nowadays, 'more circular' is often interchangeably used with 'more sustainable.' However, the term 'circular economy' remains ambitious yet ambiguous. This ambiguity includes the definition and what needs to be measured for it (Hatzfeld et al., 2022; Jerome et al., 2022; Morseletto, 2020; Nylén et al., 2023; Saidani et al., 2019). There is no universally agreed-upon concept of the circular economy, and there are various interpretations of it. It has multiple origins and is considered an umbrella concept that consists of multiple strategies and approaches. Furthermore, its connection with sustainability is not entirely clear (Bastianoni et al., 2023; Jerome et al., 2022; Moraga et al., 2019; Parchomenko et al., 2019; Rigamonti and Mancini, 2021; Saidani et al., 2019; Vadoudi et al., 2022).

(Saidani and Kim, 2022) discuss the relationship between circular economy and sustainability, highlighting three relations: 1) a conditional relation, in which circular economy is required but not sufficient to achieve sustainability, 2) a beneficial relation, in which more circularity results in more sustainability, and 3) a trade-off relation, in which the costs and benefits of circularity strategies towards sustainability need to be evaluated. The literature emphasizes that more circularity does not necessarily lead to more sustainability as there are risks of problem shifting, rebound effect, and eventually over-consumption. Therefore, there is a need to comprehensively evaluate circularity strategies (Rigamonti and Mancini, 2021).

1.3. Circularity indicators

Despite efforts to transition from a linear economy to a more circular one and the widespread exploration and implementation of circular economy in various contexts, there is no accepted monitoring framework for it, and it remains in its early stages (Parchomenko et al., 2019; Peña et al., 2021; Saadé et al., 2022). This includes the definition of the tools and criteria for measuring circularity (Elia et al., 2017). Since the circular economy is a multifaceted concept, its indicators also have different definitions (Saidani et al., 2019).

Moreover, it has been shown that existing methodologies and indicators are inadequate for monitoring all the characteristics of CE (Moraga et al., 2019), and circularity indicators often focus on specific goals or single activities (Rigamonti and Mancini, 2021). For instance, neglecting energy consumption and polluting emissions in circularity indicators can result in an incomplete view of the environmental performance of a system (Rigamonti and Mancini, 2021). Consequently, there is a need for more suitable circularity indicators that can encompass the characteristics of all circularity strategies (Rs) (Hatzfeld et al., 2022; Parchomenko et al., 2019).

According to (Corona et al., 2019), more than 300 circularity indicators were listed by the European Academies' Science Advisory Council in 2019. This extensive number may be attributed to the diverse understandings of the circular economy by different stakeholders (Corona et al., 2019). The abundance of indicators and the lack of clarity about their goals in some cases make their selection and comparison for a specific context challenging (Rigamonti and Mancini, 2021). The choice of indicators can significantly influence the decisions and perspectives of different stakeholders on the circular economy, leading to different interpretations (Parchomenko et al., 2019; Rigamonti and Mancini, 2021).

1.4. Life Cycle Assessment (LCA)

The first Life Cycle Assessment (LCA) study was conducted in the 1960s in packaging studies, primarily focused on energy use rather than emissions (Hauschild et al., 2017). Since then, it has been introduced as a methodology (Brändström and Saidani, 2022; Peña et al., 2021), a method (Bastianoni et al., 2023; Elia et al., 2017; Schulte et al., 2021; van Stijn et al., 2021), or a tool (Corona et al., 2019; Hauschild et al., 2017; van der Giesen et al., 2020). (Civancik-Uslu et al., 2018) highlight that LCA is defined as a tool by the United Nations Environment Program (UNEP) and as a methodology by the ISO standard. Additionally, (Mendoza Beltrán, 2018) points out that while LCA emerged as a method, the LCA tool has been developed over the past 30 years. As a standardized and popular method, LCA is considered the go-to approach for evaluating the environmental performance of products and services (Balanay and Halog, 2019; van Stijn et al., 2021; Vargas-Gonzalez et al., 2019). LCA can help decision-makers make more sustainable choices by providing a holistic and comprehensive perspective, offering insights not only on environmental aspects but also economic and social considerations (Peña et al., 2021; Rigamonti and Mancini, 2021).

LCA is continuously evolving, and besides the well-known prospective LCA, consequential LCA, and dynamic LCA, scholars have integrated LCA with other scientific domains, such as Blockchain LCA (Shou and Domenech, 2022), transitional LCA (Ventura, 2022), or Life Cycle Gap Analysis-LCGA (Dieterle and Viere, 2022). Sometimes, the novelty lies not only in the methodology but also in the application of LCA. A recent study by (Ellsworth-Krebs et al., 2023) is called Feminist LCA, in which a streamlined LCA is conducted to compare three hair removal methods for women: shaving, waxing, or laser.

1.5. The research aim

Both LCA and circularity assessment have been extensively reviewed in the literature. LCA is an established method, and scholars have discussed several aspects of it over the last 50 years. On the other hand, circularity strategies and indicators have also been thoroughly reviewed by various researchers, including (De Pascale et al., 2021; Elia et al., 2017; Garcia-Saravia Ortiz-de-Montellano and van der Meer, 2022; Jerome et al., 2022; Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2019; Tognato de Oliveira and Andrade Oliveira, 2023). These studies have comprehensively evaluated and categorized circularity strategies and indicators, exploring what they measure. However, the interconnections between circularity assessment and LCA have not been fully explored (Brändström and Saidani, 2022). While some aspects of LCA, such as the inclusion of the life cycle phase in circularity strategies and indicators, have been addressed in the previous literature, the synergies and gaps between circularity assessment and LCA have not been fully evaluated. To address this knowledge gap, this study is centered around the main research question: *'What are the synergies and gaps between circularity assessment and LCA?*' To answer this, the research positions both assessment methods in relation to sustainability to identify the main challenges in sustainability assessment using these methods. Therefore, two specific sub-questions were formulated to provide a comprehensive understanding of the topic: Research sub-question 1: '*What are the alignments and misalignments between circularity assessment and LCA*?' and research sub-question 2: '*What are the main challenges faced by circularity assessment and LCA in addressing sustainability*?'

By exploring these sub-questions, the study aims to shed light on the potential synergies and gaps between circularity assessment and LCA. The research outcomes, along with insights into their alignment and the opportunities for mutual learning they provide, can help researchers in the development of both LCA and circularity assessment, either as independent methodologies or in an integrated approach. These findings would be valuable for scholars in the fields of circular economy and sustainability, as well as decision-makers at various levels, including individuals, businesses, and policymakers.

2. Material and methods

To address the research question, this study utilized a two-phase method:

Phase 1. Semi-Structured Interviews: In this phase, semi-structured interviews were conducted with experts in circularity assessment, LCA, and those proficient in both domains. The interviews aimed to gather insights on the alignment and misalignment between circularity assessment and LCA. Moreover, they sought to uncover the principal challenges each approach faces in effectively addressing sustainability. The interview questions were designed to be open-ended, enabling participants to provide in-depth responses. Additionally, extra questions were dynamically adapted based on the interviewees' answers to capture unanticipated themes and explore specific aspects further. This expert-centered approach served as a screening method to identify relevant aspects and literature related to the research question.

Phase 2. Literature Review: In this phase, a literature review was undertaken, following the hybrid approach proposed by (Wohlin et al., 2022). The review process involved two steps: Primarily, digital databases such as Scopus and Google Scholar were searched using the keywords "LCA" and "circularity assessment." Furthermore, a combination of each of these two keywords with the critical elements identified in the first phase (semi-structured interviews) was used as new keywords to ensure a comprehensive search. Only peer-reviewed articles written in English and published from 2017 onwards were included in the review. In addition to the literature proposed by the expert in the first phase, snowballing (citation tracking) was conducted to trace the references cited in the selected articles. This iterative process allowed for the evaluation of the state-of-the-art literature and the addition of further layers of knowledge to the review.

3. Results

3.1. Alignments and misalignments

As an overall view, both circularity assessment and LCA aim to assess the environmental profile of products and services to enhance their sustainability. Evaluating the alignments and misalignments between the two approaches requires positioning them across different levels: philosophy, strategy, assessment, and communication.

At the philosophy level, LCA is primarily designed for a linear economy and evaluates the entire life cycle of products and services across various environmental impact categories. Its goal is to identify environmental hotspots, advantages, and burdens to make the system more sustainable. In contrast, circularity assessment aligns with the principles of the circular economy and focus on the end-of-life stage of products and services. They assess the effectiveness of different circularity strategies to foster a more circular system. (Moraga et al., 2019) point out that life cycle thinking is the heart of circular economy action in the EU.

At the strategy level, the life cycle initiative promotes that LCA can be used to evaluate circularity strategies (Saadé et al., 2022; Saidani and Kim, 2022). (Rigamonti and Mancini, 2021) discuss that LCA can contribute to developing more consistent circularity strategies by providing insights on the environmental impacts of upstream and downstream flows. For instance, (van Stijn et al., 2021) propose the Circular Economy Life Cycle Assessment (CE-LCA) model for building components, which employs LCA based on ISO standards to evaluate circularity strategies. It should be noted that evaluating a strategy does not mean defending it. (Hatzfeld et al., 2022) point out that the Life Cycle Initiative emphasizes LCA only provides sustainability assessment and does not advocate for any circularity strategy. Similarly, (Jerome et al., 2022) discuss that neither circularity indicators nor LCA fully capture the potential benefits of circularity strategies.

At the assessment level, the alignment between circularity assessment and LCA has been acknowledged by the literature (Moraga et al., 2019). The Ellen MacArthur Foundation also supports the use of circularity indicators such as the Material Circularity Index (MCI) alongside life cycle impact categories (Ellen MacArthur Foundation, 2023). (Corona et al., 2019) have distinguished between circularity indices and circularity assessment tools. In their analysis, circularity indices are for evaluating the degree of circularity of a system, but circularity assessment tools assess the effectiveness of circularity strategies. They also divided the circularity assessment tools into circularity indicators and circularity assessment frameworks. In this division, LCA has been considered as a circularity assessment framework next to Material Flow Analysis (MFA) and Input output analysis.

At the communication level, circularity assessment is considered easier to communicate (Jerome et al., 2022). (De Pascale et al., 2021) assert that circularity indicators can effectively utilize available data and knowledge to evaluate the performance of companies, sectors, or countries, thus capturing greater attention from decision-makers. While both circularity assessment and LCA can offer valuable insights to decision-makers, they may cater to different audiences (Schulte et al., 2021).

The findings of several previous studies, such as those by (Jerome et al., 2022), point to a misalignment between the results of circularity assessment and LCA. (Rigamonti and Mancini, 2021) also highlighted contradictory results of circularity assessment and LCA in most of the evaluated studies. They provided two reasons why LCA may not be capable of evaluating the circularity of a system: firstly, LCA is originally based on a linear economy from cradle to grave and is not intended for cradle-to-cradle assessments. Secondly, anthropogenic stock and dissipation flows are not considered in the modeling. On the contrary, (Hatzfeld et al., 2022) discuss that LCA's cradle-to-grave approach also incorporates recycling or energy recovery steps. The misalignment between the results of these two domains is attributed to the challenges that exist in their assessment, as further elucidated in Section 3.2.

Despite the existing misalignment, LCA should not be regarded as the primary method for assessing circularity, but rather as a complementary approach to circularity assessment (Hatzfeld et al., 2022). (Saadé et al., 2022) state that circularity assessment and LCA are complementary and should not be seen as replacements for each other. The results of a review by (Hatzfeld et al., 2022) showed complementarity with LCA is one of the four clusters of circularity assessment and circularity assessment is typically conducted after LCA. On the other hand, (Saidani and Kim, 2022) argue that circularity indicators can be effectively utilized during the design phase, while LCA would serve as a complementary approach to evaluate circularity strategies. It should be noted that the use of LCA is not restricted solely to the evaluation phase. For example, screening LCA can be employed during the design phase as a hotspot analysis to identify opportunities for eco-design.

3.2. The main challenges

3.2.1. Data availability

Performing an LCA is data-intensive (Saadé et al., 2022) and involves acquiring data from various stakeholders. This process requires a detailed examination of processes and subprocesses, making it time-consuming. To address this, several databases, like ecoinvent, have been established, providing secondary data for LCA analysis, and eliminating the need for extensive primary data collection. However, databases are built on the data for specific processes, which may lead to significant differences when evaluating a different process. Therefore, careful consideration and potential adjustments are necessary to ensure the accuracy and relevance of the LCA results.

On the other hand, (Bastianoni et al., 2019) point out that data availability for environmental assessment is relatively limited compared to the economic and social dimensions of sustainability. This limitation may influence the choice of circularity indicators, which are favored by decision-makers due to their ease of communication and computation (Jerome et al., 2022). Unlike LCA, circularity indicators do not require extensive data collection, making them more appealing for practical application.

3.2.2. Diverse assumptions

While the primary objective of LCA is to provide insights into the environmental performance of different alternatives and move beyond the ambiguity of “it depends” (Ellsworth-Krebs et al., 2023), the results of an LCA study heavily rely on the underlying assumptions. Despite being standardized in four steps, LCA results can vary significantly based on decisions made during each step. Choices such as the functional unit, system boundary (including or excluding life cycle phases like transport), and the Life Cycle Impact Assessment (LCIA) method can lead to diverse outcomes. Even with defined end-point impact categories, decision-makers often lean towards familiar environmental impact categories, such as Global Warming Potential (GWP). There is a tendency to standardize the use of a specific LCIA method across a country or region. For example, the European Commission has established the Environmental Footprint (EF) as a standardized LCIA for measuring the environmental performance of both Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) (European Commission, 2018).

The ISO 14,040 and 14,044 standards (International Organization for Standardization, 2006a, 2006b) emphasize that LCA calculates the “potential,” not actual, environmental impacts (Schaubroeck et al., 2021). LCA is inherently accompanied by uncertainty, common to any modeling process. Extensive research, including the pioneering works of Mark Huijbregts (Huijbregts, 1998a, 1998b), has explored the sources of uncertainty in LCA studies. These sources include data inaccuracy, data gaps, unrepresentative data, methodological choices, models, spatial and temporal variability. (Peña et al., 2021) highlight the lack of consistent modeling for open recycling loops as an example of modeling uncertainty. Similarly, (Schulz et al., 2020) discuss the lack of guidelines for repurposing strategies in LCA studies.

Regarding circularity assessment, the study by (Brändström and Saidani, 2022) indicates a high dependency on assumptions. These assumptions involve factors such as the defined system boundary, product lifetime, sharing efficiency, recycling rate, and linearity of the reference scenario. Furthermore, numerous sector-specific circularity indicators exist, such as those for the building sector (Cottafava and Ritzen, 2021; Khadim et al., 2022, 2023) or the agri-food sector (Harchaoui et al., 2023; Poponi et al., 2022; Priyadarshini and Abhilash, 2023). Overall, circularity indicators are still evolving, and standardization in this area is yet to be achieved (Hatzfeld et al., 2022).

3.2.3. The spotlights and shadows

Traditionally, circularity assessments have been criticized for their narrow focus, either on the starting point (resource efficiency and use of renewable sources) or on the endpoint (recycling and use of secondary raw materials). In a comprehensive review of circularity strategies and indicators, (De Pascale et al., 2021) highlighted that circularity indicators are primarily developed around recycling practices. (Hatzfeld et al., 2022) raised concerns about an excessive emphasis on waste minimization, which may result in overlooking opportunities to avoid generating unrecoverable waste in the first place. Furthermore, the act of recycling often leads to downcycling in many cases, which presents challenges for circularity assessment. Similar challenges were faced by LCA during its evolution into the methodology used today. (Bhander et al., 2003), two decades ago, emphasized the need for LCA to shift its focus from the “end-of-pipe” solutions to a more holistic consideration of the entire life cycle of products and processes.

Circularity assessments primarily focus on materials and their preservation (Parchomenko et al., 2019). A comprehensive review by (Moraga et al., 2019) evaluated the scope of circularity assessments, revealing that they directly or indirectly target various aspects, including function, product, components, materials, and embodied energy, as well as with reference scenarios. Researchers have also attempted to itemize the core elements of circularity assessments. For example, a comprehensive study by (Parchomenko et al., 2019) identified four common elements in circularity assessments: waste disposal, primary vs. secondary use, resource efficiency/productivity, and recycling efficiency. Similarly, (Hatzfeld et al., 2022) categorized their characteristics into multi-cyclic longevity, up- & downcycling, measuring disruptive change, and complementarity with LCA.

The evaluation of circularity assessment can be conducted at different levels or scales, as explored by multiple authors (Hatzfeld et al., 2022; Moraga et al., 2019; Rigamonti and Mancini, 2021; Saidani et al., 2019). These levels typically encompass micro-level assessments (e.g., products, services, firms, and consumers), meso-level evaluations (e.g., eco-industrial systems), and macro-level analyses (e.g., national, global, or industry-wide structures). Additionally, some researchers, such as (Hatzfeld et al., 2022) and (Khadim et al., 2022), have also considered a nano-level assessment (e.g., materials). When assessing the circularity of a product, the assessment evaluates its capability to retain both the quantity and quality of materials. Conversely, when assessing a company's circularity, it signifies the transition from a linear to a circular business model (Rigamonti and Mancini, 2021). The selection of circularity indicators naturally depends on the level of assessment. For instance, circularity indicators like MCI are typically applied at the nano or micro levels, focusing on materials and products.

While certain CE indicators differentiate between renewable and non-renewable energy resources, they often overlook critical factors such as scarcity, criticality, or toxicity of materials (Jerome et al., 2022). On the other hand, LCA encompasses environmental impact categories like Abiotic Resource Depletion or those addressing material scarcity (currently under development), providing a more comprehensive view of the environmental implications (Hatzfeld et al., 2022).

Likewise, social aspects are seldom addressed in circularity assessments (Hatzfeld et al., 2022), despite the existence of an established methodology for analyzing social impacts through Social Life Cycle Assessment (s-LCA). The UNEP (2020) has provided clear guidelines for conducting s-LCA, making it a valuable tool for evaluating the social dimension of sustainability in the life cycles of products and services.

In the past, primary environmental assessments focused on single impact categories like cumulative energy demand or carbon footprint. However, widely used life cycle impact assessment methods, such as ReCiPe 2016 (Global) (Huijbregts et al., 2017) and Environmental Footprint (Europe) (European Commission, 2018), now cover various midpoint impact categories. As discussed (Schaubroeck et al., 2021), the traditional environmental impacts in LCA have been limited to three areas of protection: human health, natural resources, and ecosystems. Recent research has introduced new impact categories, such as noise in the Ecological Scarcity 2021 impact method (Federal Office for the Environment, 2021) and animal welfare (Turner et al., 2023). Despite efforts to include more impact categories, achieving a correct and comprehensive assessment remains challenging (Vanham et al., 2019). For example, a comprehensive analysis by (Damiani et al., 2023) of published methods and models for biodiversity impact assessment revealed that no single method encompasses all required aspects simultaneously, even though some methods excel in addressing specific biodiversity aspects. Furthermore, the study by (Vanham et al., 2019) highlighted overlaps between various environmental impact categories, which is particularly relevant when conducting a comprehensive assessment and integrating different impact metrics. Considering the continual discovery of new environmental and health impacts resulting from our current consumption and production patterns, the development of environmental impact categories remains crucially important.

3.2.4. Multiple life cycles, products, functions, and strategies

Multiplicity is undoubtedly one of the most challenging issues encountered in both LCA and circularity assessment. This complexity from the need to handle multiple life cycles, products, functions, and strategies within the assessment framework. It is quite common to encounter situations where multiple products are involved in more than one life cycle and serve different functions, making the modeling inherently intricate.

For multiple life cycles, circularity assessments typically focus on either a retrospective or prospective cycle, considering only one life cycle (Hatzfeld et al., 2022). In this context, the process of slowing down or closing the loop has occurred in the past (for reused/recycled products) and may occur in the future (for reusable/recyclable products) (Shevchenko et al., 2023). Nonetheless, the Ellen MacArthur Foundation emphasizes that LCA should encompass multiple life cycles to effectively evaluate circularity (Hatzfeld et al., 2022). Including several life cycles is crucial for LCA to provide a comprehensive view of the circularity of the system (Stillitano et al., 2022). Despite this, there are no clear guidelines for handling multiple material uses in LCA (Haupt and Zschokke, 2017). The study conducted by (Jerome et al., 2022) reveals that circularity strategies aimed at extending the product lifetime are not adequately addressed in circularity assessments. One possible reason for this omission is the lack of consideration for maintenance in these assessments (Hatzfeld et al., 2022). To address the issue of multiple life cycles, (van Stijn et al., 2021) developed their CE-LCA model using system expansion and an equal distribution approach.

The ISO standard 14,044 (International Organization for Standardization, 2006b) provides clear guidelines on how to handle multiple products and allocation in LCA. It prioritizes specific approaches, beginning with avoiding allocation through subdivision and, if not feasible, then employing system expansion. The next step involves allocation based on physical properties, and finally, allocation can be based on other relationships, such as economic value. When dealing with recycling, an important question arises regarding the allocation of benefits and burdens between the primary and secondary products. To address this, the European Commission has standardized allocation rules using the Circular Footprint Formula (CFF) for recycling, reusing, or recovering energy (European Commission, 2018; Zampori and Pant, 2019). The topic of allocation has been extensively discussed within the LCA society (Corona et al., 2019; Hauschild et al., 2017; Moretti et al., 2022).

It should be noted that when referring to LCA in general, attributional LCA is the focus. Attributional LCA aims to determine the environmental impacts that can be attributed to the studied product and models the product system in isolation from the rest of the technosphere and economy, using average processes for the background systems. On the other hand, consequential LCA seeks to evaluate the environmental consequences of consuming the studied product by modeling the changes to the economy resulting from its introduction. Unlike attributional LCA, consequential LCA uses marginal processes for the background systems (Hauschild et al., 2017). The selection between these two models has been an ongoing topic of discussion in the LCA community.

Unlike LCA, circularity assessments typically do not account for the function of products. (Jerome et al., 2022) highlight the importance of using the function as the basis of comparison for resource-related effects from circularity strategies. Their review highlights that only a limited number of circularity indicators incorporate both function and temporal aspects. Similarly, (Hatzfeld et al., 2022) emphasize the need to move beyond the focus on either products or materials in circularity assessments and stress the importance of considering functionality. By incorporating functionality into LCA, cumulative environmental impacts, such as GWP, can be calculated for multiple product systems across their multiple lifecycles. To address this, they introduce the concept of Functionality Over Use-Time (FOUT) and propose functional and cross-functional circularity indicators. Additionally, they introduce Functional Half-Life (FHL), inspired by half-life in nuclear physics, to measure the time it takes for a product to lose half of its functionality. Using FHL allows for the comparison of products with entirely different functions.

Regarding circularity strategies, the study by (Jerome et al., 2022) reveals that circularity indicators can be categorized as either single-focus, targeting one specific strategy, or multi-focus, considering multiple strategies. Notably, material recycling emerges as the primary focus for both single-focus and multi-focus circularity indicators. While single-focus indicators are easier to interpret, they may not encompass all life cycle phases and flows, making them unsuitable for capturing burden-shifting issues. Furthermore, neither single-focus nor multi-focus CE indicators fully address the entire circular economy concept, as noted by (Brändström and Saidani, 2022; Jerome et al., 2022).

To provide an overview of the discussions in this section, Table 1 compares different circularity strategies (Rs) based on their targeted life cycle, product, and function. The selection of these strategies is based on the report by the PBL Netherlands Environmental Assessment Agency, and they are arranged in order of priority (Potting et al., 2017). In this analysis, the arrangements of three elements for each R strategy are assessed: the life cycle, the product, and the function. To facilitate this evaluation, the life cycle is categorized into two types: maintaining the same life cycle or adopting a new one. The same life cycle can, in turn, be associated with either the same duration or an extended lifespan. Similarly, the product and function are classified as either maintaining the same or introducing new ones.

For the Refuse strategy (R0), the goal is to abandon the function, whether for the same or a new product, within the same life cycle. In the Rethink strategy (R1), the focus is on intensive product use, with either the existing or a new function. The Reduce strategy (R2) aims for efficient manufacturing and product use, reducing resource and material consumption while maintaining the same product and function within the same life cycle.

In the Re-use strategy (R3), the product is reused with its original function after being discarded. The Repair strategy (R4) also focuses on

Table 1
Comparison of different circularity strategies in terms of their targeted life cycles, products, and functions.

Strategy	Life cycle			Product/function			
	The same life cycle	The same life cycle, but an extended lifespan	A new life cycle	The same product with the same function	The same product with a new function	A new product with the same function	A new product with a different function
R0) Refuse	✓			✓		✓	
R1) Rethink	✓			✓	✓		
R2) Reduce	✓			✓			
R3) Re-use		✓		✓			
R4) Repair		✓		✓			
R5) Refurbish		✓		✓			
R6) Remanufacture		✓				✓	
R7) Repurpose		✓					✓
R8) Recycle			✓	✓		✓	✓
R9) Recover			✓				✓

the same product and function but extends the product's lifespan. Similarly, the Refurbish strategy (R5) aims to prolong the lifespan of the same product while maintaining its original function. On the other hand, the Remanufacture strategy (R6) seeks to prolong the product's lifespan while maintaining its original functionality, essentially creating a new product. It should be noted that the original function of the product is preserved, and in some cases, even enhanced, but without introducing new functions. The Repurpose strategy (R7) involves using discarded products or their parts to create a new product with a new function.

The Recycle (R8) strategy aims for a new lifecycle, where both the product and its function can undergo changes. When recycling is directed towards reproducing the same product, it is referred to as closed-loop recycling, while recycling for a new product is known as open-loop recycling. In closed-loop recycling, the same product with the same function is maintained, but in the case of open-loop recycling, both products and functions can change. The final recommended strategy in the hierarchy is the Recover (R9) strategy, primarily focused on energy recovery.

3.2.5. Temporal aspects

The temporal aspect is one of the most challenging, considered, and yet probably not fully resolved issues in LCA (Cardellini et al., 2018). Fig. 1 illustrates a schematic of the temporal aspect in LCA. While life cycle thinking aims to go beyond the present point and consider both the past and future, time is a multifaceted aspect in LCA. It involves the lifetime of the products under study, the time of conducting the assessment, the times when the environmental impacts begin and end, and the timeframe of the assessment itself. These aspects are further explored in the following subsections.

LCA studies are constrained by their system boundaries, which means that they may not cover all life cycle phases of the studied product. For instance, when conducting an LCA for Product A (see Fig. 1), the analysis would encompass the entire life cycle, including the phases of extraction, production, distribution, use, and end-of-life. However, when comparing its environmental performance with an alternative, such as Product B, a direct one-on-one comparison may not be equitable if Product B has a different lifetime. To address this challenge, LCA studies define a functional unit as a basis for comparison. The functional unit allows for fair comparisons by focusing on the function of the products rather than their physical quantities or lifetimes. This approach enables the evaluation of different product systems with the same function, providing a more accurate and equitable assessment of their environmental impacts.

The environmental impacts of products extend beyond their life cycles, and it is essential to distinguish between the lifetime of a product and the time frame of assessment. As highlighted by (Levasseur et al., 2010) in an example, consider a building with a 75-year lifetime. Throughout its life cycle, there are three points when emissions from this building may occur: at the beginning (time zero), after 25 years, or at the end of its 75-year lifespan. In this context, if we choose a time frame of assessment of 100 years, it only covers 100 years of emissions from this building that began at time zero. For the emissions starting after 25 years, only 75 years of emissions are included in our assessment. Similarly, for emissions beginning after 75 years, only 25 years are included in our assessment. This indicates that the emissions occurring after 25 years or at the end of the building's life are partially captured within the defined 100-year assessment period. Therefore, it is evident that the starting points of emissions and the time frame of assessment may differ, and it is crucial to consider this temporal aspect when conducting environmental assessments.

Different time horizons in the assessment have been addressed by the LCIA method. For example, the ReCiPe 2016 methodology considers three timeframes: 20, 100, and 1000 years for calculating GWP from three perspectives: individualist, hierarchist, and egalitarian, respectively (Huijbregts et al., 2017). Similarly, the IPCC 2021 LCIA, developed by the Intergovernmental Panel on Climate Change (IPCC), also

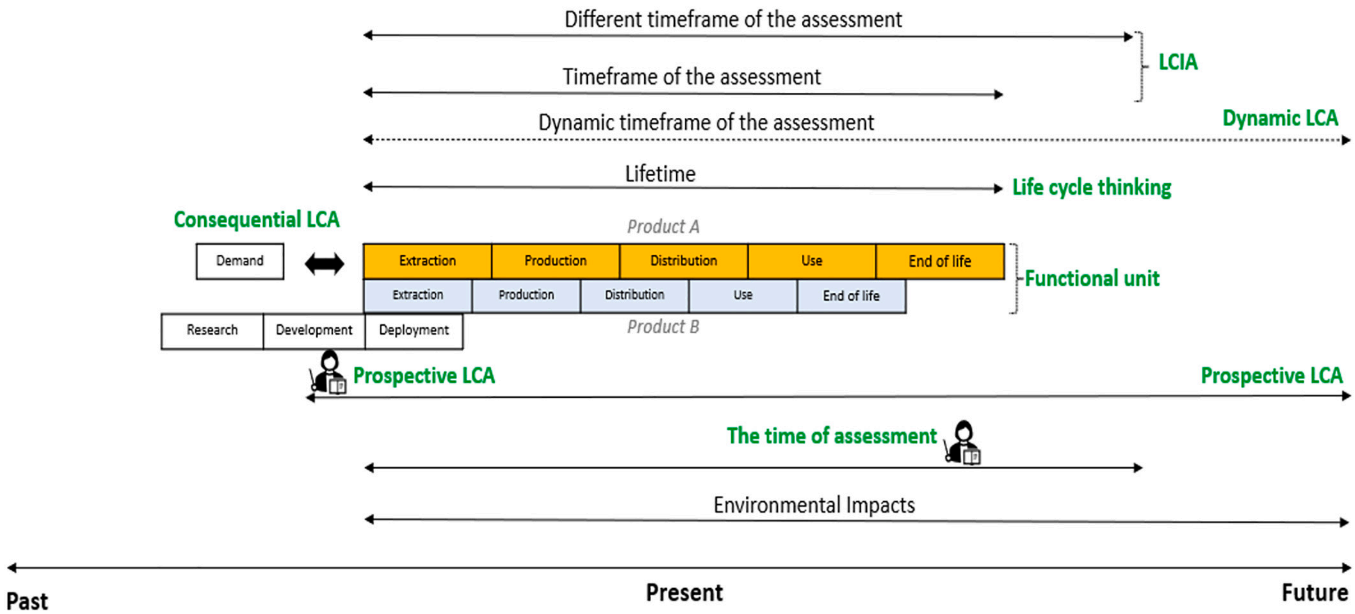


Fig. 1. Schematic of the temporal aspects in LCA.

includes three timeframes: 20, 100, and 500 years (Intergovernmental Panel on Climate Change, 2021). The selection of the timeframe has a significant impact on the results of LCA studies. For instance, according to the IPCC 2021 LCIA, the characterization factors for methane are almost 8 times higher in the 20-year timeframe and 3 times higher in the 100-year timeframe when compared with the 500-year timeframe. This difference can be attributed to the short lifetime of methane (around 12 years), which results in a more pronounced impact in shorter assessment timeframes.

Dynamic LCA has been established to address the timeframe of assessment mentioned earlier. This method incorporates the temporal dimension in both the Life Cycle Inventory (LCI) and LCIA, but within a fixed timeframe of assessment (Cucurachi et al., 2022; Levasseur et al., 2010). It involves including the temporal dimension in the definition of the functional unit during the goal and scope definition, considering the temporal relationship between flows in the LCI, and utilizing dynamic characterization factors and weighting, such as discounting, in the LCIA (Cardellini et al., 2018). Numerous scientific works, like the study conducted by (Beloin-Saint-Pierre et al., 2020), have explored dynamic LCA as a means to address the temporal aspect in life cycle assessment studies.

In addition to the temporal aspects discussed earlier, the timing of the assessment is also crucial in LCA studies. While conducting an LCA based on the current model provides insights into improving the sustainability of a product system, evaluating future changes in technological systems can be challenging. To address this, prospective LCA has been established, which focuses on evaluating emerging technologies in their early development stages during the research and development phase. This method involves developing future scenarios to model the system at a later time, addressing higher Technology Readiness Levels (TRLs) (Arvidsson et al., 2018). Prospective LCA encompasses all the steps of classic LCA and includes scenarios for both foreground and background systems. Prospective LCA, also known as ex-ante LCA, is used for analyzing future scenarios, whereas retrospective LCA, or ex-post LCA, is based on actual results from past events (Cucurachi et al., 2018; Hauschild et al., 2017). (Cucurachi et al., 2022) emphasize that the term ex-ante should be used specifically when addressing LCA applied to emerging technologies transitioning from laboratory to commercial scale. It is essential to note that prospective LCA explores future possibilities but does not predict them; it involves developing future scenarios to understand potential impacts (Cucurachi et al., 2018).

4. Discussion

To address the first research sub-question regarding the alignment and misalignment between circularity assessment and LCA, this analysis underscores the need for a multi-level approach to examine their interconnections. It cautions against hastily concluding that these two approaches are either fully aligned or entirely distinct. The analysis involves positioning these approaches at different levels, including philosophy, strategy, assessment, and communication.

It is important to emphasize that the circular economy has evolved based on the lessons learned from life cycle thinking. For circularity strategies, both LCA and circularity assessment can serve as methods for sustainability assessment, despite the existing gaps. Importantly, neither of these approaches can provide a complete picture of the environmental performance of a system on its own. Uncertainty is an inseparable element of LCA, circularity assessment, and any other modeling. As George Box once said, 'All models are wrong, some are useful.' Depending on the scope of the assessment, different beneficial outcomes can be extracted from both assessment methods. If either of these methods fails to capture the environmental profile for a specific circularity practice, it indicates the need to examine what we can learn from the outcomes and how their results can complement each other. Moreover, it is crucial to recognize that their alignment does not necessarily mean their results will indicate the same (e.g., the superiority of alternative A over alternative B). Circularity assessment and LCA are indeed two complementary approaches that ultimately aim to facilitate more sustainable decisions. When used together, they can provide valuable insights and support the transition towards a more circular and sustainable society.

To address the second research sub-question concerning the main challenges faced by circularity assessment and LCA in addressing sustainability, five key issues were identified: data availability, diverse assumptions, spotlights and shadows (highlighted and neglected elements), multiple life cycles, products, functions, and strategies, and temporal aspects.

Data availability remains a significant challenge for any sustainability assessment. LCA, being data-intensive, relies on available databases, which are often not ideal but still useful. Circularity assessments have an advantage in this regard, as they are less data-intensive and, hence, more popular. Nonetheless, the development of databases specific to circularity indicators, especially for different materials and specific sectors, would greatly benefit designers and sustainability practitioners.

Standardization and diverse assumptions are other challenges faced by both LCA and circularity assessment. LCA has made more progress in standardization, but it is crucial to communicate the dependency of results on the modeling and its assumptions to the audience. As the ISO 14,040 standard emphasizes, sensitivity and uncertainty analyses are essential for providing clarity in LCA. Additionally, transparently providing the LCI data is crucial for enhancing the understanding and credibility of LCA results. For circularity assessment, similar practices of transparency and standardization are essential. It is vital to specify what aspects, such as energy use and emissions, are not covered in the assessment to avoid misinterpretation of the results. Moreover, recognizing that a one-size-fits-all approach, similar to the GWP in LCA, may not be appropriate for circularity indicators across different sectors.

The spotlights and shadows section emphasized that circularity indicators evaluate various elements at different life cycle phases and levels, debunking the myth that they solely focus on end-of-life and materials. They have a wide application, ranging from nano to macro levels. Examining both the highlighted and neglected points aids in comprehending the strengths and limitations of circularity and sustainability assessments, with the inclusion of social and economic aspects making it even more significant.

The challenge of dealing with multiple life cycles, products, functions, and strategies has been thoroughly explored, highlighting the interconnectedness of these elements. This understanding holds significant value when assessing circularity strategies using circularity indicators, LCA, or an integrated approach. In the examination of different R strategies, the first three (R0, R1, and R2) are linked to the same life cycle, while R3 to R7 seek to extend the lifespan, and R8 and R9 relate to a new life cycle. Nevertheless, how these strategies target either the same or a new product, or whether they serve the same or an entirely different function, can vary significantly. Emphasizing the consideration of function in the analysis aligns with previous research findings (Hatzfeld et al., 2022; Jerome et al., 2022). Furthermore, this analysis is firmly grounded in the definitions of these Rs as outlined by (Potting et al., 2017), but they may diverge based on alternative interpretations. For instance, the Rethink (R1) strategy could potentially be interpreted in ways that extend beyond the confines of the same life cycle or product.

The temporal aspect, which is a major challenge for both approaches, has been extensively discussed in the LCA community. Concepts such as function and functional unit, prospective LCA to evaluate the future scenarios, and dynamic LCA to address variable timeframes have been developed, providing valuable insights for circularity assessment experts to incorporate into future circularity assessments.

One criticism of the circular economy is the potential for overconsumption in its ideal state. Previous research aims to connect circular economy concepts with global frameworks like planetary boundaries and Sustainable Development Goals (SDGs). Notably, (Sala et al., 2020) evaluated the alignments between LCA, planetary boundaries, and SDGs. Other literature (Bergmark and Zachrisson, 2022; Kometsopha, 2018; Vanham et al., 2019; Vargas-Gonzalez et al., 2019) also explores the connections between LCA and planetary boundaries. (Vanham et al., 2019) discuss how environmental impact categories can assess society's adherence to or surpassing planetary boundaries. The Joint Research Centre (JRC) of the European Commission aligned global environmental impacts and planetary boundaries for defining normalization factors in LCA (Sala et al., 2016). Regarding the SDGs, (Tognato de Oliveira and Andrade Oliveira, 2023) explore their relationship with circularity principles and indicators. Similarly, (Garcia-Saravia Ortiz-de-Montellano et al., 2023) conducted a comprehensive analysis, demonstrating how circularity strategies contribute to the advancement of the SDGs. These research efforts highlight the significance of adopting a holistic and systemic perspective in the context of the circular economy. As emphasized by (Bastianoni et al., 2019), having such a perspective is crucial in ensuring that a circularity assessment provides a comprehensive understanding, akin to seeing the entire forest rather than just individual trees.

There are still numerous topics for future research to explore and advance in the field of sustainability assessment. In the current methodologies of LCA and circularity assessment, the focus is often on physical flows, and the actors involved in these processes are not fully taken into account (Böckin et al., 2022). Consequential LCA has been developed to address the inclusion of the rest of the technosphere and economy. Meanwhile, Life Cycle Management (LCM) has attempted to integrate LCA with business models and include those actors. Therefore, future research could delve into how a model based on LCA and/or circularity assessment can effectively assess circular business models.

5. Conclusions

This article aimed to evaluate the synergies between circularity assessment and LCA by investigating their alignments, misalignments, and the challenges they face in addressing sustainability. Overall, the findings indicate that circularity assessment and LCA are complementary assessment methods, providing a comprehensive understanding of environmental sustainability when integrated. To enhance sustainability assessments, adopting a holistic view and exploring integration with other approaches are essential. The results also revealed various opportunities for learning from each other, despite the existing challenges in both methods.

The main challenges faced by circularity assessment and LCA in addressing sustainability include data availability, diverse assumptions, spotlights and shadows (highlighted and neglected elements), multiple life cycles, products, functions, strategies, and temporal aspects. To overcome these challenges, function-based models and the principles of prospective and dynamic LCAs can provide valuable insights for the development of future circularity indicators. Additionally, circularity assessment can be used to establish LCA models, helping to identify hotspots during the goal and scope definition and determine the allocation and weighting factors in both LCI and LCIA. By leveraging the strengths of both approaches and addressing these challenges, we can achieve a more comprehensive understanding of environmental sustainability and make informed decisions towards a circular and sustainable future.

CRediT authorship contribution statement

Pouya Samani: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

Acknowledgment

I would like to thank my colleagues at the Circularity and Sustainability Impact (CSI) department of TNO for their valuable insights and support.

References

Arvidsson, R., Tillman, A.M., Sandén, B.A., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2018. Environmental assessment of emerging technologies: recommendations for prospective LCA. J. Ind. Ecol. 22, 1286–1294. https://doi.org/10.1111/jiec.12690.

Balanay, R., Halog, A., 2019. Tools for circular economy: review and some potential applications for the Philippine textile industry. In: Circular Economy in Textiles and Apparel: Processing, Manufacturing, and Design. Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102630-4.00003-0.

Bastianoni, S., Coscieme, L., Caro, D., Marchettini, N., Pulselli, F.M., 2019. The needs of sustainability: the overarching contribution of systems approach. Ecol. Indic. 100, 69–73. https://doi.org/10.1016/j.ecolind.2018.08.024.

Bastianoni, S., Goffetti, G., Neri, E., Patrizi, N., Ruini, A., Sporchia, F., Pulselli, F.M., 2023. LCA based circularity indices of systems at different scales: a holistic approach. Sci. Total Environ. 897, 165245 https://doi.org/10.1016/j.scitotenv.2023.165245.

Beloin-Saint-Pierre, D., Albers, A., Hélias, A., Tiruta-Barna, L., Fantke, P., Levasseur, A., Benetto, E., Benoist, A., Collet, P., 2020. Addressing temporal considerations in life cycle assessment. Sci. Total Environ. 743 https://doi.org/10.1016/j.scitotenv.2020.140700.

Bergmark, P., Zachrisson, G., 2022. Towards considering planetary boundaries in life cycle assessments of ICT. In: 2022 International Conference on ICT for Sustainability, ICT4S 2022. IEEE, pp. 128–139. https://doi.org/10.1109/ICT4S55073.2022.00024.

Bhander, G.S., Hauschild, M., McAloone, T., 2003. Implementing Life Cycle Assessment in product development. Environ. Prog. 22, 255–267. https://doi.org/10.1002/ep.670220414.

Böckin, D., Goffetti, G., Baumann, H., Tillman, A.M., Zobel, T., 2022. Business model life cycle assessment: a method for analysing the environmental performance of business. Sustain. Prod. Consum. 32, 112–124. https://doi.org/10.1016/j.spc.2022.04.014.

Brandão, M., Lazarevic, D., Finnveden, G., 2020. Handbook of the Circular Economy. Edward Elgar Publishing, Inc. https://doi.org/10.4337/9781788972727

Brändström, J., Saidani, M., 2022. Comparison between circularity metrics and LCA: a case study on circular economy strategies. J. Clean. Prod. 371 https://doi.org/10.1016/j.jclepro.2022.133537.

Cardellini, G., Mutel, C.L., Vial, E., Muys, B., 2018. Temporalis, a generic method and tool for dynamic Life Cycle Assessment. Sci. Total Environ. 645, 585–595. https://doi.org/10.1016/j.scitotenv.2018.07.044.

Circle Economy, 2023. The Circular Gap Report 2023. Deloitte, Amsterdam.

Civancik-Uslu, D., Ferrer, L., Puig, R., Fullana-i-Palmer, P., 2018. Are functional fillers improving environmental behavior of plastics? A review on LCA studies. Sci. Total Environ. 626, 927–940. https://doi.org/10.1016/j.scitotenv.2018.01.149.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498 https://doi.org/10.1016/j.resconrec.2019.104498.

Cottafava, D., Ritzen, M., 2021. Circularity indicator for residentials buildings: addressing the gap between embodied impacts and design aspects. Resour. Conserv. Recycl. 164, 105120 https://doi.org/10.1016/j.resconrec.2020.105120.

Cucurachi, S., Van Der Giesen, C., Guinée, J., 2018. Ex-ante LCA of emerging technologies. Procedia CIRP 69, 463–468. https://doi.org/10.1016/j.procir.2017.11.005.

Cucurachi, S., Steubing, B., Siebler, F., Navarre, N., Caldeira, C., Sala, S., 2022. Prospective LCA methodology for novel and emerging technologies for BIO-based products. In: European Commission - JRC Technical Report. https://doi.org/10.2760/695092.

Damiani, M., Sinkko, T., Caldeira, C., Tosches, D., Robuchon, M., Sala, S., 2023. Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context. Environ. Impact Assess. Rev. 101, 107134 https://doi.org/10.1016/j.eiar.2023.107134.

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G., 2021. A systematic review for measuring circular economy: the 61 indicators. J. Clean. Prod. 281 https://doi.org/10.1016/j.jclepro.2020.124942.

Dieterle, M., Viere, T., 2022. Life cycle gap analysis for product circularity and sustainability—a case study with three different products. Mater. Circ. Econ. 4, 1–8. https://doi.org/10.1007/s42824-022-00055-5.

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196.

Ellen MacArthur Foundation, 2023. Material Circularity Indicator [WWW Document]. https://ellenmacarthurfoundation.org/material-circularity-indicator. (Accessed 19 July 2023).

Ellsworth-Krebs, K., Niero, M., Jack, T., 2023. Feminist LCAs: finding leverage points for wellbeing within planetary boundaries. Sustain. Prod. Consum. 39, 546–555. https://doi.org/10.1016/j.spc.2023.05.035.

European Commission, 2018. Product Environmental Footprint Category Rules Guidance. PEFCR Guid, Doc.

Federal Office for the Environment, 2021. Swiss Eco-factors 2021 According to the Ecological Scarcity Method-methodological Fundamentals and Their Application in Switzerland.

Garcia-Saravia Ortiz-de-Montellano, C., van der Meer, Y., 2022. A theoretical framework for circular processes and circular impacts through a comprehensive review of indicators. Glob. J. Flex. Syst. Manag. 23, 291–314. https://doi.org/10.1007/s40171-022-00300-5.

Garcia-Saravia Ortiz-de-Montellano, C., Samani, P., Van Der Meer, Y., 2023. How can the circular economy support the advancement of the sustainable development goals? A comprehensive analysis. Sustain. Prod. Consum. 40, 352–362. https://doi.org/10.1016/j.spc.2023.07.003.

Harchaoui, S., Blazy, V., Péchenart, E., Wilfart, A., 2023. Challenges and opportunities for improving circularity in the poultry meat and egg sector: the case of France. Resour. Conserv. Recycl. 193 https://doi.org/10.1016/j.resconrec.2023.106963.

Hatzfeld, T., Backes, J.G., Guenther, E., Traverso, M., 2022. Modeling circularity as functionality over use-time to reflect on circularity indicator challenges and identify new indicators for the circular economy. J. Clean. Prod. 379, 134797 https://doi.org/10.1016/j.jclepro.2022.134797.

Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. Int. J. Life Cycle Assess. 22, 832–837. https://doi.org/10.1007/s11367-017-1267-1.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2017. Life Cycle Assessment: Theory and Practice. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3

Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D., Hollander, A., Zijp, M., van Zelm, R., 2017. ReCiPe 2016 v1.1. National Institute for Public Health and the Environment (RIVM).

Huijbregts, M.A.J., 1998a. Application of uncertainty and variability in LCA. Part I: a general framework for the analysis of uncertainty and variability in life cycle assessment. Int. J. Life Cycle Assess. 3, 273–280. https://doi.org/10.1007/BF02979835.

Huijbregts, M.A.J., 1998b. Application of uncertainty and variability in LCA: part II: dealing with parameter uncertainty and uncertainty due to choices in life cycle assessment. Int. J. Life Cycle Assess. 3, 343–351. https://doi.org/10.1007/BF02979345.

Intergovernmental Panel on Climate Change, 2021. Climate Change 2021 – The Physical Science Basis. In: Climate Change 2021 – The Physical Science Basis. https://doi.org/10.1017/9781009157896.

International Organization for Standardization, 2006a. ISO 14040, Environmental Management — Life Cycle Assessment — Principles and Framework.

International Organization for Standardization, 2006b. ISO 14044, Environmental Management — Life cycle assessment — Requirements and Guidelines.

Jerome, A., Helander, H., Ljunggren, M., Janssen, M., 2022. Mapping and testing circular economy product-level indicators: a critical review. Resour. Conserv. Recycl. 178, 106080 https://doi.org/10.1016/j.resconrec.2021.106080.

Khadim, N., Agliata, R., Marino, A., Thaheem, M.J., Mollo, L., 2022. Critical review of nano and micro-level building circularity indicators and frameworks. J. Clean. Prod. 357, 131859 https://doi.org/10.1016/j.jclepro.2022.131859.

Khadim, N., Agliata, R., Thaheem, M.J., Mollo, L., 2023. Whole building circularity indicator: a circular economy assessment framework for promoting circularity and sustainability in buildings and construction. Build. Environ. 241, 110498 https://doi.org/10.1016/j.buildenv.2023.110498.

Kometsopha, P., 2018. Linking the Planetary Boundaries to the Life Cycle Environmental Impacts of Cotton T-shirts in the Netherlands. Utrecht University.

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., Samson, R., 2010. Considering time in LCA: dynamic LCA and its application to global warming impact assessments. Environ. Sci. Technol. 44, 3169–3174. https://doi.org/10.1021/es9030003.

Mendoza Beltrán, M.A., 2018. Deepening the Uncertainty Dimension of Environmental Life Cycle Assessment. Addressing Choice, Future and Interpretation Uncertainties. Leiden University.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: what do they measure? Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045.

Moretti, C., Corona, B., Hoefnagels, R., van Veen, M., Vural-Gürsel, I., Strating, T., Gosselink, R., Junginger, M., 2022. Kraft lignin as a bio-based ingredient for Dutch asphalts: an attributional LCA. Sci. Total Environ. 806 https://doi.org/10.1016/j.scitotenv.2021.150316.

Morseletto, P., 2020. Targets for a circular economy. Resour. Conserv. Recycl. 153, 104553 https://doi.org/10.1016/j.resconrec.2019.104553.

Nylén, E.J., Johanson, J.E., Vakkuri, J., 2023. The loop from idealised to messy – untangling ideational features of the circular economy and hybridity in its making. Environ. Sci. Pol. 140, 146–151. https://doi.org/10.1016/j.envsci.2022.11.023.

Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H., 2019. Measuring the circular economy - a multiple correspondence analysis of 63 metrics. J. Clean. Prod. 210, 200–216. https://doi.org/10.1016/j.jclepro.2018.10.357.

Peña, C., Civit, B., Gallego-Schmid, A., Druckman, A., Caldeira-Pires, A., Weidema, B., Mieras, E., Wang, F., Fava, J., Canals, L.M.I., Cordella, M., Arbuckle, P., Valdivia, S., Fallaha, S., Motta, W., 2021. Using life cycle assessment to achieve a circular economy. Int. J. Life Cycle Assess. 26, 215–220. https://doi.org/10.1007/s11367-020-01856-z.

Poponi, S., Arcese, G., Pacchera, F., Martucci, O., 2022. Evaluating the transition to the circular economy in the agri-food sector: selection of indicators. Resour. Conserv. Recycl. 176, 105916 https://doi.org/10.1016/j.resconrec.2021.105916.

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation in the Product Chain. PBL Netherlands Environmental Assessment Agency, The Hague.

Priyadarshini, P., Abhilash, P.C., 2023. An empirical analysis of resource efficiency and circularity within the agri-food sector of India. J. Clean. Prod. 385, 135660 https://doi.org/10.1016/j.jclepro.2022.135660.

Rigamonti, L., Mancini, E., 2021. Life cycle assessment and circularity indicators. Int. J. Life Cycle Assess. 26, 1937–1942. https://doi.org/10.1007/s11367-021-01966-2.

Saadé, M., Erradhouani, B., Pawlak, S., Appendino, F., Peuportier, B., Roux, C., 2022. Combining circular and LCA indicators for the early design of urban projects. Int. J. Life Cycle Assess. 27, 1–19. https://doi.org/10.1007/s11367-021-02007-8.

Saidani, M., Kim, H., 2022. Nexus between life cycle assessment, circularity, and sustainability indicators—part I: a review. Circ. Econ. Sustain. 2, 1143–1156. https://doi.org/10.1007/s43615-022-00159-9.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.

Sala, S., Benini, L., Crenna, E., Secchi, M., 2016. Global environmental impacts and planetary boundaries in LCA. https://doi.org/10.2788/64552.

Sala, S., Crenna, E., Secchi, M., Sanyé-Mengual, E., 2020. Environmental sustainability of European production and consumption assessed against planetary boundaries. J. Environ. Manag. 269 https://doi.org/10.1016/j.jenvman.2020.110686.

Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., Benetto, E., 2021. Attributional & consequential life cycle assessment: definitions, conceptual characteristics and modelling restrictions. Sustainability 13, 1–47. https://doi.org/10.3390/su13137386.

Schulte, A., Maga, D., Thonemann, N., 2021. Combining life cycle assessment and circularity assessment to analyze environmental impacts of the medical remanufacturing of electrophysiology catheters. Sustainability 13, 1–23. https://doi.org/10.3390/su13020898.

Schulz, M., Bey, N., Niero, M., Hauschild, M., 2020. Circular economy considerations in choices of LCA methodology: how to handle EV battery repurposing? Procedia CIRP 90, 182–186. https://doi.org/10.1016/j.procir.2020.01.134.

Shevchenko, T., Saidani, M., Ranjbari, M., Kronenberg, J., Danko, Y., Laitala, K., 2023. Consumer behavior in the circular economy: developing a product-centric framework. J. Clean. Prod. 384, 135568 https://doi.org/10.1016/j.jclepro.2022.135568.

Shou, M., Domenech, T., 2022. Integrating LCA and blockchain technology to promote circular fashion – a case study of leather handbags. J. Clean. Prod. 373, 133557 https://doi.org/10.1016/j.jclepro.2022.133557.

Stillitano, T., Falcone, G., Iofrida, N., Spada, E., Gulisano, G., De Luca, A.I., 2022. A customized multi-cycle model for measuring the sustainability of circular pathways in agri-food supply chains. Sci. Total Environ. 844, 157229 https://doi.org/10.1016/j.scitotenv.2022.157229.

Tognato de Oliveira, C., Andrade Oliveira, G.G., 2023. What circular economy indicators really measure? An overview of circular economy principles and sustainable development goals. Resour. Conserv. Recycl. 190, 106850 https://doi.org/10.1016/j.resconrec.2022.106850.

Turner, I., Heidari, D., Widowski, T., Pelletier, N., 2023. Development of a life cycle impact assessment methodology for animal welfare with an application in the poultry industry. Sustain. Prod. Consum. 40, 30–47. https://doi.org/10.1016/j.spc.2023.06.010.

UNEP, 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations 2020.

Vadoudi, K., Deckers, P., Demuytere, C., Askanian, H., Verney, V., 2022. Comparing a material circularity indicator to life cycle assessment: the case of a three-layer plastic packaging. Sustain. Prod. Consum. 33, 820–830. https://doi.org/10.1016/j.spc.2022.08.004.

van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G.J., Tukker, A., 2020. A critical view on the current application of LCA for new technologies and recommendations for improved practice. J. Clean. Prod. 259 https://doi.org/10.1016/j.jclepro.2020.120904.

van Stijn, A., Malabi Eberhardt, L.C., Wouterszoon Jansen, B., Meijer, A., 2021. A circular economy Life Cycle Assessment (CE-LCA) model for building components. Resour. Conserv. Recycl. 174 https://doi.org/10.1016/j.resconrec.2021.105683.

Vanham, D., Leip, A., Galli, A., Kastner, T., Bruckner, M., Uwizeye, A., van Dijk, K., Ercin, E., Dalin, C., Brandão, M., Bastianoni, S., Fang, K., Leach, A., Chapagain, A., Van der Velde, M., Sala, S., Pant, R., Mancini, L., Monforti-Ferrario, F., Carmona-Garcia, G., Marques, A., Weiss, F., Hoekstra, A.Y., 2019. Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. Sci. Total Environ. 693 https://doi.org/10.1016/j.scitotenv.2019.133642.

Vargas-Gonzalez, M., Witte, F., Martz, P., Gilbert, L., Humbert, S., Jolliet, O., van Zelm, R., L'Haridon, J., 2019. Operational life cycle impact assessment weighting factors based on planetary boundaries: applied to cosmetic products. Ecol. Indic. 107, 105498 https://doi.org/10.1016/j.ecolind.2019.105498.

Ventura, A., 2022. Transition life cycle assessment: a new method to face ecological transition. Front. Sustain. 3 https://doi.org/10.3389/frsus.2022.801668.

Wohlin, C., Kalinowski, M., Romero Felizardo, K., Mendes, E., 2022. Successful combination of database search and snowballing for identification of primary studies in systematic literature studies. Inf. Softw. Technol. 147, 106908 https://doi.org/10.1016/j.infsof.2022.106908.

Zampori, L., Pant, R., 2019. Suggestions for Updating the Product Environmental Footprint (PEF) Method. Publications Office of the European Union. https://doi.org/10.2760/424613.