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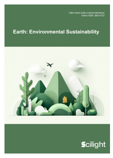

Opinion

The Frontiers in Life Cycle Assessment Considering Materials Circularity

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Abstract: The accelerating global transition towards a circular economy necessitates a fundamental rethinking of how we assess environmental impacts, particularly through Life Cycle Assessment (LCA). Traditional LCA frameworks are largely linear, assessing the environmental burdens of products from cradle to grave. However, in an era where circularity is a policy goal and industrial practice, there is a growing need to reformulate LCA to effectively capture closed-loop systems, multiple product life cycles, and dynamic material flows. This opinion paper outlines the critical frontiers in LCA research and practice needed to address materials circularity, highlighting methodological innovations, integration challenges, and the role of digital technologies in enabling circular thinking within life cycle frameworks. The paper is based on peer-reviewed studies from four academic databases, using the keywords: "Life Cycle Assessment", "Circular Economy", "food valorization", "food loss", and "food waste". Findings reveal that while several circularity indicators have emerged, traditional LCA often fails to account for avoided emissions, particularly in perishable goods.

Keywords: life cycle assessment; materials circularity; digital technologies; circular economy; environmental indicators; sustainability assessment; resource efficiency; reuse and repurposing

1. Introduction—The Circular Imperative

The circular economy (CE) approach has become an imperative part of national strategies and action plans, with the most notable being the EU Circular Economy Action Plan. This action plan outlines legislative and non-legislative measures to decouple economic growth from resource use with targeted actions across the entire life cycle of products. Shifting towards CE requires fundamental changes in the value chain system and challenges the restructuring from the traditional linear model of "take, make, dispose," to keeping materials and resources in use for as long as possible and extracting maximum value from them while in use. Materials circularity is a core component of the circular economy that involves designing out waste, promoting reuse, extending product lifespans, and enabling effective end-of-life recovery.

There are many ways a product can stay within the circular system. Zorpas [1], for instance, identifies 100 distinct "R-strategies" (e.g., reuse, remanufacturing, recycling, repurposing, refurbishing, etc.) that contribute to circularity. However, it is essential to differentiate the environmental and resource implications of each strategy. Not all circular actions offer the same level of environmental benefit, and their effectiveness depends largely on context and execution.

This paper is structured as an opinion paper, reviewing the current methodological frontiers in LCA for circularity, combined with a conceptual proposal on how perishable products and the reuse of other products shall be accounted as avoided emissions. This effort is in line with the EU Circular Economy Action Plan and the UN Sustainable Development Goals, both of which emphasize the need for improving resource efficiency, advancing waste prevention strategies, and promoting responsible production patterns. By proposing adjustments in LCA application and especially for perishable products, a novel approach can be adopted that "rewards" food loss and waste prevention with reduced emissions.

2. Tools and Indicators for Assessing Circularity

Several methods have been developed for assessing the circularity of a product or service, including the use of key performance indicators (KPIs) such as recycling rates, product lifespan extension, and resource efficiency metrics. However, for these assessments to be meaningful and accurate, it is crucial to clearly define the system boundaries. Circularity assessments primarily focus on material and their preservation with four key elements commonly identified: (i) waste disposal, (ii) resource efficiency, (iii) primary versus secondary use, and (iv) the recycling efficiency [2]. Hatzfeld et. al. [3] presented a categorization for circularity evaluations based on three characteristics: (i) multi-cyclic longevity, (ii) up- and downcycling, and (iii) alignment with LCA frameworks.

The most known methods for evaluating how efficiently resources are retained, reused, or cycled through a system include, but are not limited to, the Material Circularity Indicator (MCI) and Circulytics that have been developed by the Ellen MacArthur Foundation. These methods work together to assess the material flows of a product or company and identify the strategies, operations and innovations at the organizational level. Similarly, Circular Transition Indicators (CTI) by the World Business Council for Sustainable Development (WBCSD) is an Excel-based toolkit and guidance documentation that measures a company's circular performance with a set of standardized indicators. Developed by the European Department of Environment, the European Platform on Life Cycle Assessment (EPLCA) moves a step back, evaluating the product development phase in a qualitative format, such as: design for durability, ease of disassembly, recycling potential, etc. [4]. Recently, in 2024, the ISO 59020:2024(en), framework has emerged with a structural scope in measuring and assessing circularity performance of organizations across various levels of an economic system [5]. Table 1 summarizes the differences between the circularity indicators in terms of their use and their functional opportunities/drawbacks.

Table 1. Comparative Overview of Circularity Indicators.

Indicator	Developer	Focus/Scope	Advantages	Limitations
Material Circularity Indicator (MCI)	Ellen MacArthur Foundation	Product-level circularity (recycled content, product lifespan, recovery rate)	Easy to calculate; widely recognized; applicable at product/company level	Does not capture environmental impacts; limited sectoral adaptability
Circulytics	Ellen MacArthur Foundation	Company-level transition towards circular economy	Comprehensive assessment (strategy, operations, innovation); broad applicability	Qualitative; limited comparability between organizations
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Circular Transition Indicators (CTI)	WBCSD	Company circular performance, material flows	Excel-based toolkit; standardized metrics; GHG impact calculation	Focused on company operations
ISO 59020:2024	International Organization for Standardization	Organizational circularity performance across sectors	Global standard; harmonization of circularity measurement; applicable at different system levels	Still emerging; requires significant data input (water, energy, resources flow etc.)

3. Life Cycle Assessment: Traditional Role and Emerging Challenges

A more traditional approach to measuring circularity can be found in the Lifecycle Assessment (LCA) method, that quantitatively integrates circularity into environmental impact assessments. These methods excel in the provisioning of more informative analysis for strategic development and mitigation measures adopting a holistic approach, that encompass all stages, from raw material extraction and processing to manufacturing, transportation and environmental performance, use, and end-of-life management [6]. The LCA methodology has been instrumental in quantifying environmental impacts throughout a product's life cycle. Originating in the 1960s and maturing through ISO standards in the 1990s, LCA has primarily served linear production models: resource extraction, manufacturing, use, and disposal. As society transitions towards a circular economy, a core strategy for reducing environmental impacts and safeguarding both renewable and non-renewable resources, this linear framework is increasingly insufficient. LCA can serve as a pivotal tool in the transition towards a circular economy, offering a systematic methodology for quantifying the environmental burdens and benefits associated with a product or service throughout its entire life cycle [7]. An important aspect of LCA is that it can provide a comprehensive multi-stage analysis, encompassing resource depletion, toxicity, carbon footprint, and even social impacts through its social extension (s-LCA) [8,9].

The pursuit of materials circularity has propelled LCA into a critical juncture, demanding a re-evaluation of its methodologies and boundaries to effectively capture the nuances of circular systems [10]. Traditional LCA, often rooted in linear models, defines strict system boundaries from resource extraction ("cradle") to disposal ("grave"), with recycling and reuse often treated as end-of-life scenarios rather than integrated system behaviors. To successfully implement LCA into CE scenarios, the inherent limitations must be faced, and developing innovative approaches to address the complexities of extended product lifecycles, multiple loops, and cascading material flows is necessary. The integration of circular economy principles within LCA frameworks requires a comprehensive understanding of material flows, energy consumption, and environmental impacts across multiple life cycles as it transitions to "cradle-to-cradle" thinking.

Therefore, an evolutionary approach is required to expand the system boundaries of LCA, to encompass not only the production and end-of-life stages but also the reuse, remanufacturing, and recycling processes that define circularity [8]. Besides those practices, central to the circular economy, also lies the effective utilization of materials through maximizing their value during use, prolonging their life, increasing the recovery rate and their residual value at the end of their useful lives [11]. As an example to this perspective, the construction sector accounts for a significant environmental footprint, stemming from extensive resource extraction and waste production. Employing LCA and taking into advantage the ability to precisely identify opportunities for enhanced resource management and the reduction of waste streams can facilitate the shift towards more sustainable construction practices that promote resource efficiency [12]. A study carried out by Gomes et al. [13] in architecture students has shown that making the necessary modifications in product and service design to enhance lifespan, maintainability, and recyclability can reduce the environmental consequences associated with building material flows. In the same context, material selection also arises as a pivotal factor in determining the circularity performance of a building, significantly influencing its ability to be recirculated and endure through reuse, remanufacturing, refurbishment or recycling, hinging on its material processability and durability.

Circular strategies in the construction sector often include using reclaimed concrete aggregates, salvaged timber, or modular design for disassembly. This is especially important as the focus lies on extending the use of building materials that are often in short supply. In that context, "handprint" thinking emerged in the construction industry. A handprint shows the positive environmental impact a project has, based on the three main aspects of sustainability: environment, social, and economic [14]. The environmental aspect represents the sum of GHG emissions and removals in the product system expressed as CO_2 equivalents, providing an incentive of utilization by the intended user. However, the study also points out that there isn't a fully standardized LCA to measure all the parts of a carbon handprint yet, such as carbon storage, carbon sequestration, or the benefits of reuse.

As mentioned earlier, LCA has long been the gold standard for evaluating the environmental impacts of products from the point of raw material extraction, up to the end of life. However, its role in supporting CE models, especially for consumable goods, it remains unclear and can be debated. The sole purpose of CE strategy is to keep products and materials in use, extending their lifespan by implementing the 'R' strategies, leading to a reduction in the need for primary material consumption and lessening the strain on natural resources. Yet, the linear nature of LCA methodologies may overlook system-wide benefits like avoided production and resource use. This paper argues that to align with circular principles, LCA frameworks should be restructured to better account for reuse or repurpose strategies and explicitly incorporate avoided emissions, especially in the case of perishable products. Specifically, the paper aims to:

I. identify methodological gaps in standard LCA when applied to reuse and repurposing strategies,
II. highlight the need for consequential LCA in accounting for avoided burdens, and
III. propose how sector-specific applications, especially in food repurposing, can promote and incentivize the adoption of circular economy strategies.

Literature review was carried out across peer-reviewed journals, policy reports, and industry publications with a specific focus on Life Cycle Assessment (LCA), food valorization, and methodological tools for circular economy assessment. Particular attention was given to studies addressing food loss and waste, which exhibit the methodological challenges and practical implications when embedded in circular economy strategies. Concerning the database selection, four databases were chosen: Science Direct, Scopus, Wiley, and Web of Science, to sample articles using the following keywords: “Life Cycle Assessment”, “Circular Economy”, “food valorization”, “food loss”, and “food waste”. These academic sources were complemented by policy documents from the European Union and the United Nations to maintain relevance with current regulations and sustainability policies.

LCA excels at quantifying the environmental footprint of various agricultural production systems and assessing the end-of-life scenarios of the produced items, mainly landfilling, anaerobic digestion, and composting. However, this approach tends to fall short when evaluating “reuse” in the circular sense. Reuse can be viewed as a waste prevention process if it occurs amongst multiple users before the product is discarded. It can also be considered the best option from an economic point of view for the farmers and companies that manage discarded agricultural products. As the route of reusing prevents landfilling or anaerobic digestion of products, it can also be seen as the most environmentally favorable route. Only the fraction of materials that cannot be reused due to safety regulations or critically low quality should be directed to disposal, ensuring that all viable resources remain within the circular loop.

Most LCA approaches treat reuse as a process burden without sufficiently crediting the potential environmental gains it offers by offsetting the need for the production of new products. A review study carried out by Abagnato et al. [15] in reuse and recycling practices, they found that 44% of the studies define the functional unit is as ‘*the treatment or the management of a certain amount of MSW, of textile waste or of textile products addressed to reuse centers before they become waste*’. In theory, the environmental burden associated with the extraction and production of raw materials is already accounted for during the initial life cycle of the original product. Therefore, when the product undergoes processing to be Itransformed into a new product, the environmental impact assessment should focus solely on the new production process.

This approach works well, especially for non-biodegradable products that can be repurposed long after their initial use, such as metals like iron or aluminum. These materials maintain their physical integrity over time, allowing for repurposing without immediate degradation or loss of function. However, this logic may not apply as effectively to biodegradable or perishable materials, such as food or organic waste. In these cases, the materials would have decomposed or been discarded without timely intervention. For example, the production of ready-made soups, jams, or sauces typically requires significant quantities of fresh vegetables or fruits. If cosmetically imperfect or surplus produce that would otherwise be destined for disposal, they have the potential to be diverted from waste streams and repurposed into these products, achieving a triple benefit: (i) The environmental cost of growing additional produce, and (ii) the creation of additional economic stream and (iii) the retention of nutritional and calorific value in the products’ life cycle. In the context of environmental cost, repurposing food waste means preventing further resource use and reducing the need for expanding agricultural land. Thus, the LCA boundaries of environmental accounting in the case of perishable products must also consider the avoided impacts of otherwise necessary virgin production. This is not just food rescue; it is emissions avoidance through resource substitution.

For example, a tomato that is deemed unsellable due to imperfection but is still edible would often be discarded and likely end up in a landfill, releasing methane, and requiring more tomatoes to be grown for future products. But if that same tomato is processed into added-value product, such as tomato sauce, it can replace the need for an equivalent amount of freshly grown tomatoes in the field. By repurposing unmarketable tomatoes, the food supply chain avoids growing, processing, packaging, and transporting a new tomato that would have been used for sauce production. This “displacement” effect is both tangible and measurable, and brings up the argument for balancing out the potential environmental impact against the emissions that are avoided by not having to grow, harvest, package, and transport additional agricultural products. To exclude them is to undervalue reuse and miss the forest for the trees, as the benefits of circular practices are underscored. Thus, by adjusting the LCA equation to incorporate avoided emissions, we get a more comprehensive and accurate representation of environmental outcomes of repurposing strategies [16,17].

$$\text{Net Impact of Reuse} = \text{Direct Emissions from Processing} - \text{Avoided Emissions from Virgin Production} \\ - \text{Avoided Emissions from Waste Disposal}$$

A strategy of minimizing wasted food has proven to yield the most substantial reduction across all the environmental impact categories [18]. Having the tools to properly quantify this impact is essential to serve as a powerful incentive for communities, industries, and policymakers to adopt circular practices. Demonstrating and recognizing the environmental benefits of reuse not only justifies circular interventions but also encourages broader participation and investment in sustainable resource management.

To avoid not capturing the benefits of avoided emissions in the case of reuse or repurposing and encourage circular practices, the consequential LCA (CLCA) methodology is preferred. Consequential LCA aims to describe how environmental flows will change as a result of a decision or intervention, such as choosing to reuse materials or investing in new infrastructure [19]. In contrast, Attributional LCA (ALCA) differ significantly as it seeks to describe the environmentally relevant physical flows (e.g., emissions, resource use) directly associated with a product's life cycle, estimating the environmental burden "attributed" to a product or service under average conditions, often using allocation methods to divide impacts among co-products [20]. Therefore, since we are assessing reuse systems and aiming to capture the avoided burdens (e.g., reduced virgin material), consequential LCA offers a more appropriate framework allowing the estimation of the actual environmental benefits of circular practices, including system-level changes and long-term effects. A recent study by Sandin et al. [21] explored the environmental potential of diverting 10% of discarded textiles into existing recycling routes of textile-to-textile in Europe. The results showed that it can result in a 0.5% reduction in climate change impacts and 3.3% in water deprivation of textile products bought in Europe.

This approach is increasingly supported by guidelines. The European Commission's Joint Research Centre [22] acknowledges the validity of accounting for avoided burdens in comparative assessments of end-of-life options [22]. Similarly, ISO 14044 (the international standard for LCA) allows for "system expansion" to account for avoided impacts, particularly when comparing functionally equivalent systems.

A proposed framework is conceptualized in Figure 1, presenting a five-step structured pathway to operationalize the integration of circularity indicators with consequential LCA, thereby effectively informing and adapting decision-making and policy-making. The first and most important step includes the definition of the System Boundaries, where a cradle-to-cradle approach is adopted, and raw materials or rejected perishable products are excluded. The avoided and disposal emissions are then accounted for in the LCA analysis to quantify the remaining environmental flows and burdens of the new process/product (e.g., repurposing, valorization). Complementary circularity indicators can also be incorporated in the analysis in a vice-versa format, either by drawing data from LCA or by informing the LCA, to capture additional dimensions like material recirculation, product lifespan, and resource efficiency. The combination of LCA and circularity insights can inform policy frameworks and certification schemes, but also allows for any reforms of policies that may redefine the system boundaries in line with evolving circular economy objectives.

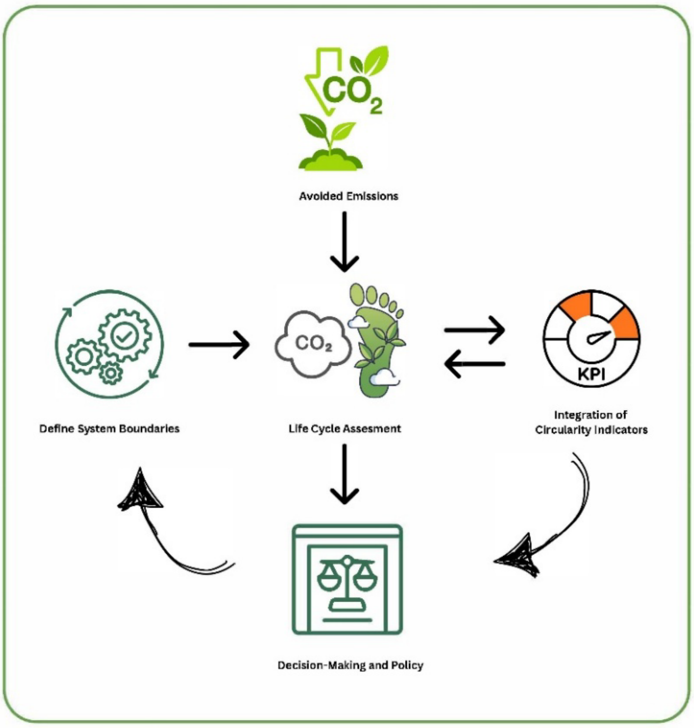

Figure 1. Complementing LCA with Circularity Indicators.

Application of the LCA though, doesn't come without limitations and issues, with the risk of double-counting being a key component. Double counting may occur when environmental benefits or burdens are allocated more than once across different product systems. Among the particular cases in the issue may arise is when credits for avoided impacts are assigned both to the producer of secondary materials and to the user of those materials. This is also prominent when multiple recycling, reuse, or other circular strategies are integrated in the system boundaries without a clear and detailed process description; this may lead to overrepresentation in flows, obscuring the true net environmental performance.

For example, if food losses are valorized through food processing, and any resulting residues are further utilized as animal feed, the environmental credits must be properly allocated to each use with an appropriate allocation method. In the construction sector, reclaimed building materials used in multiple subsequent projects may similarly be over-credited if the modeling does not carefully account for material quality degradation or substitution effects. Therefore, when developing an LCA system, the allocation of environmental benefits must be transparently explained, and system boundaries must be clearly defined.

4. Complementing LCA with Circularity Indicators

The LCA does not provide sufficient information on how a product or technology will perform in the future. LCA may evaluate the environmental effect of a product or process, but its conclusions do not yet show how circular a solution is and at what level. Thus, incorporating quantitative circularity indicates may bridge this gap, as they can assess the circularity of resources and material flows in LCA. The functionality and prospect of integrating LCA with circularity indicators such as the MCI and the MRS can further support decision making and comprehensive assessment of a product or company/service [23,24]. Circularity indicators are generally easier to communicate and have the ability to drive the transition to circularity at the product or company level. This potential integration can cover the weak spots and any possible inconsistencies in applying avoided burdens that can obscure the true environmental profile.

A prime example is a comparison conducted by Lindgreen et al. [23], between plastic (PET) and glass bottles. To assess the circularity of products, authors assessed the restorative flow of the system by employing MCI, which incorporates variables such as % recyclable product and % recycled content in the product. Even though glass bottles scored higher in terms of circularity due to their reuse potential, LCA revealed the hidden environmental burden as they contribute significantly more to global warming than PET. This paradox illustrates that a product's circularity efficiency does not always equate to environmental superiority. This proves that LCA serves as a necessary counterbalance, preventing overreliance on CE indicators that could otherwise mislead sustainability strategies.

5. Digital Innovation and Real-Time Circular LCA

New emerging technologies and digitalization are reshaping material tracking and enabling more accurate, real-time data collection, which can further support this integration. For instance, a farmer could implement a blockchain system to trace surplus or substandard produce across the value chain. Each batch's origin, quality, and storage conditions can be recorded in real time and stored securely, enabling precise data input into a circular LCA model. In the case where a certain batch is redirected from direct consumption due to imperfections, AI algorithms can evaluate different end-of-life scenarios to identify the route with the lowest environmental impact. If the product is deemed suitable for processing, it is diverted away from the waste stream and transformed into value-added goods. Such integration offers informed, data-driven decisions that optimize resource use, reduce food waste, and add economic value, while at the same time, the system enhances transparency and accountability, ensuring the adoption of the most circular approach [25].

6. Conclusions

LCA is indispensable in assessing the true environmental performance of circular economy strategies, but must it evolve if it is to remain a relevant and robust decision-making tool in the age of circular economy. LCA methodologies should formally recognize avoided emissions in reuse scenarios, especially in food systems. Reuse in food systems is often penalized due to assessments that overlook the environmental "savings" from displacing virgin production and preventing harmful end-of-life outcomes. The high production intensity in food systems coexists with high levels of perishable waste, reflecting the necessity to develop and incentivize reduction and repurposing strategies by systematically including the displacement benefits of those practices. This shift would not only promote better waste-to-value strategies but also inform smarter policy-making and business models. Policy makers could suggest new amendments for the environmental product declarations (EPDs) and circular economy directives to formally calculate and recognize the benefits of reusing and repurposing strategies, and more importantly, in the food industry. At the industry level, it would encourage innovations in logistics, processing, and community food systems that prioritize maximizing utility from all edible goods. Implementation of digital tracking and data-sharing systems (e.g., blockchain, IoT) by the stakeholders could improve the transparency in the Food Supply chain and build consumers' trust in the circular products.

The rising environmental pressures make the integration of LCA into Circular Indicators a necessity to offer a robust, science-based framework for quantifying environmental impacts and circularity of a product's life cycle or a service strategy. When effectively combined with circularity indicators, this approach does more than support sustainability goals; it reveals trade-offs, exposes unintended consequences, and guides more informed and impactful decisions.

However, the lack of quantitative assessment, along with the specific focus given on the sectors of food loss and waste valorization and the construction industry, poses the main limitations of this study. Therefore, future research should examine the proposed LCA approach across a broader range of sectors, such as textiles, electronics, etc., to further exploit the potential use within circular economy strategies. Additionally, studies should focus on the quantitative evaluation of sector-specific consequential LCA methodologies that account for avoided environmental burdens and displacement effects in products. Comparative analysis with traditional production methods and conventional attributional LCA approaches is also recommended to identify any potential miscounting or overlap in impact attribution.

Author Contributions

F.E: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing-original draft, Writing—Review & Editing.; I.V.: Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing-original draft, Writing—Review & Editing, Visualization; P.L: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing-original draft, Writing—Review & Editing.; M.S.: Conceptualization, Formal analysis, Resources, Data curation, Writing—Review & Editing, Visualization.; V.N. Conceptualization, Validation, Formal analysis, Investigation, Resources, Data curation, Writing—Review & Editing, Visualization.; V.P: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing-original draft, Writing—Review & Editing.; C.G.S.: Methodology, Validation, Writing—Review & Editing; N.T.: Methodology, Validation, Writing—Review & Editing; A.A.Z: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing-original draft, Writing—Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-assisted Technologies

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