Challenges, Innovations, and Future Directions in Life Cycle Assessment of Product and Process Impacts

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Reliable estimation of the environmental impacts of processes and products is essential for achieving the Sustainable Development Goals. Life cycle assessment (LCA) is a key method for evaluating such effects. Since its development, the concept has evolved to improve the precision of the obtained results. In addition to software tools, various focuses are available that consider factors such as sustainability, social aspects, and organizational perspectives. Beyond the advancements made, there is still a need for improvement in developing accurate models and frameworks. In this sense, developments such as new information technologies can be key players in the field.

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In recent years, the environmental impacts of human activities have become a key aspect of the Sustainable Development Goals. It is essential to evaluate all inputs and outputs of an activity or process to quantify their effects. Similarly, a biobased economy has begun to emerge to address the environmental concerns associated with the impacts of conventional processes, particularly those involving fossil-based products. One of the main tools for environmental assessment is Life Cycle Assessment (LCA).

LCA emerged in the 1970s to evaluate energy analysis, with pioneering well-known studies, such as the Coca-Cola and Ecobalance assessment, developed to assess aspects such as energy efficiency and emissions in beverage containers. Since the concept's development, LCA has evolved over the last decades, driven by advancements in methodologies, technologies, and sustainability priorities. Early LCA methods were limited in scope. Therefore, the trend has been moving towards incorporating increasingly complex systems into the analysis. The primary challenges in LCA for determining product and process emissions involve defining system boundaries, especially in identifying relevant upstream and downstream processes such as raw material extraction, conversion, and end-of-life treatment. LCA studies typically also lack information on supply chain steps and emerging technologies, which are critical for accurately quantifying emissions (Fig. 1).

As a result of these trends, conducting an LCA can be a very data-intensive and time-consuming task. This has led some to develop and use databases such as open LCA, SimaPro, and Ecoinvent, which provide quality-checked life cycle inventory and assessment information to plug into the calculations.

Fig. 1. Valorization chain involved in an LCA

Approaches that can make relatively less complex assessments, such as water and carbon footprints or Product Carbon Flow (PCF), have gained attention in the last decade. These metrics can evaluate specific impacts, *e.g.*, greenhouse gas (GHG) emissions, by focusing on a single impact and quantifying potential reductions in emissions. These approaches don't consider other environmental emissions such as ozone depletion, land use, and acidification. For example, the assessment of biopolyethylene and bioethanol, compared with polyethylene ($KgCO_2e$/kg product) and gasoline ($KgCO_2e$/MJ product) from fossil sources, shows a considerable reduction in GHG emissions; however, factors such as land use, eutrophication, and acidification are still better when selecting the fossil route (Luo *et al.* 2009; Ita-nagy *et al.* 2020; Sarisky-Reed 2022; Clauser *et al.* 2025).

To promote consistency and reliability, an ISO standard has been developed, which defines methodologies and approaches for LCA analysis (ISO 14040 and 14044). Additionally, frameworks such as GLAM 1.0 (2024) provide standardized methods for evaluating impacts on ecosystems, human health, and socio-economic assets. In this way, several related assessments including Life Cycle Sustainability Assessments (LCSA), Social Life Cycle Assessments (S-LCA), Organizational Life Cycle Assessments (OLCA), Organizational Life Cycle Sustainability Assessments (OLCSA), Life cycle costing (LCC), and other Circularity Assessment Frameworks reflect efforts to address specific sustainability challenges (Table 1).

Table 1. Brief Comments about LCA Methods (Pati 2022; UNEP 2025)

Method	Focus
LCC	Focuses on all costs associated with a product's life cycle.
S-LCA	Complements LCA and LCC by focusing on the social and sociological aspects of products.
OLCA	Assesses the environmental impacts of an organization's activities and its product portfolio. This methodology typically addresses multiple objectives.
OLCSA	Integrates economic, social, and environmental impacts at the organizational level.
LCSA	Evaluates the environmental, social, and economic impacts (both negative and positive) of products throughout their life cycle. Usually includes S-LCA and LCC.
Dynamic LCA	Assesses impacts using time-dependent data and models.
pLCA	Estimates future environmental impacts of emerging technologies at early development stages.

In addition to traditional LCA methods, several promising multidimensional approaches are emerging. Two of the most promising trends are prospective LCA and dynamic LCA. Prospective Life Cycle Assessment (pLCA) aims to evaluate the future environmental impacts of emerging technologies during their early stages of development. It attempts to model scenarios that account for factors such as energy sources, policies, regulations, and market dynamics. These models must incorporate, among other things, uncertainties related to market trends, future policy developments, and technological evolution. One of the main challenges lies in managing the uncertainties associated with process design under future conditions, such as feedstock availability, energy source mix, and conversion yields, as well as broader variables like policy changes, consumer behavior, and market trends. Dynamic LCA addresses the limitations of static LCA by accounting for temporal and spatial variations in its assessments. This approach relies on time-sensitive data and must integrate models that can reflect energy demand over time, seasonal material flows, and variations in emissions. Key challenges in this area include developing complex models, defining appropriate time horizons, improving real-time data availability, and creating new methodological frameworks.

LCA must deliver robust studies, enhance methods for uncertainty assessment, align with evolving policy frameworks, and incorporate emerging technologies and standardized methodologies. The integration of information technologies, such as the Internet of Things (IoT), artificial intelligence (AI), Big Data, and machine learning (ML), offers promising opportunities to improve data collection, standardization, and uncertainty reduction. Recent studies using AI-driven LCA showed higher prediction accuracy in environmental impacts (Li *et al.* 2024; Shafiq *et al.* 2024) and a considerable decrease in assessment time (Shafiq *et al.* 2024).

LCA continues to evolve and strengthen environmental assessments, with new implementations and models emerging to address challenges and bridge existing knowledge gaps.

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