

## Proposed Life Cycle Engineering Framework for Emerging Bioprocesses

Stephanie de Melo Santana<sup>1\*</sup>, Fernando Luiz Pellegrini Pessoa<sup>2</sup>, Hugo Gomes Damato Villardi<sup>2</sup>, Danilo Jefferson Romero<sup>1</sup>  
<sup>1</sup>SENAI CIMATEC University, Agroindustry Department; <sup>2</sup>SENAI CIMATEC University, Chemical Department, Salvador, Bahia, Brazil

**This study explores the application of Life Cycle Engineering (LCE) as a means to assess the sustainability of emergent bioprocesses, with a focus on biofuel production. A distinction has been made between LCE and another life cycle-based concept, Life Cycle Assessment (LCA), highlighting LCE as a more comprehensive approach that encompasses social, environmental, and economic aspects. The study is theoretical in nature, drawing on a literature review on both LCE and the *Agave*-based ethanol production process to propose a framework for applying LCE in low Technology Readiness Level (TRL) bioprocesses, aligning with the 7th and 9th Sustainable Development Goals.**

**Keywords:** Life Cycle Engineering. Bioprocesses. *Agave*. Ethanol. Sustainable Development Goals.

**Abbreviations:** IEA, International Energy Agency. ISO, International Organization for Standardization. LCA, Life Cycle Assessment. LCE, Life Cycle Engineering. TRL, Technology Readiness Level.

According to the IEA's (International Energy Agency) report, Brazil is considered one of the global leaders in the bioenergy sector, being the second-largest producer of bioethanol, the third-largest producer of biodiesel, and the world's largest producer of second-generation ethanol [1,2]. The estimated production of these biofuels in 2022 was 36.89 billion liters, increasing to 42.91 billion liters in 2023 [3]. As this is the main driver of the bioeconomy in this country, the Brazilian government issued two decrees in 2024 to establish the National Bioeconomy Strategy and the National Circular Economy Strategy. The first one aims to align industrial development, biotechnology, and agricultural production with sustainable economic development, and the second one encourages reuse and recycling of materials, waste reduction, and efficient resource use [4,5].

An emerging concept within the field of sustainability is bioeconomy, which refers to an economic model based on strengthening the use of renewable resources and applying biotechnology within production chains [4,6].

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Address for correspondence: Stephanie de Melo Santana. Rua 15 de Janeiro – Recreio de Ipitanga, Lauro de Freitas, Bahia, Brazil. Zipcode: 4272-1800. E-mail: sms.teca@gmail.com.

With the rise of this concept, there has been a growing body of research focused on biomass processing, mainly as an alternative to fossil-based sources to mitigate the impacts of climate change. Nevertheless, there are still barriers to innovation in bioprocesses, such as high costs, food security concerns, land use conflicts, the generation of low value-added co-products anwaste, water consumption, and biodiversity loss. This highlights the fact that it is not sufficient for raw materials to be renewable; it is essential to assess sustainability comprehensively throughout the entire production cycle and find sources that can endure climate changes [6,7].

To ensure that such guidelines are effectively implemented, tools are needed to support changes in industry and to aid in the design of new processes, especially regarding the need for circular chains.

Life Cycle Assessment (LCA) is the most widely used approach for measuring the environmental impacts associated with a product and it is one of several methods based on Life Cycle Thinking, standardized by ISO 14040 and 14044. LCA can evaluate the various phases of a product's life cycle, from raw material cultivation to end-of-life (recycling or disposal) or focus on selected stages. Since LCA primarily addresses environmental aspects, similar approaches have been developed to assess economic costs and social impacts as well [8].

In the 1990s, a new approach began to be discussed that would enable the integration of social, environmental, and economic aspects with a focus on designing cleaner processes. This approach is known as Life Cycle Engineering (LCE), a concept similar to LCA but involving a holistic study that encompasses the development of the product, with a techno-economic focus that does not exclude environmental and social considerations [9]. If effectively applied to bioprocesses, LCE could help ensure that a project can meet the United Nation's Sustainable Development Goals (SDGs) 7 and 9, concerning the use of renewable resources, economic growth, and the promotion of innovation and infrastructure for more sustainable industries [10].

The objective of this study was to demonstrate how the concept of LCE is defined within the field, identifying the most relevant aspects to outline a step-by-step procedure for its application in bioprocesses with low Technology Readiness Levels (TRL), with the aim of assessing their sustainability and feasibility.

## Materials and Methods

The bibliographic review was primarily conducted using the Scopus database. While additional sources such as ScienceDirect, Google Scholar, Scielo, and CAPES Periodicals were also consulted, Scopus was selected as the main source due to its comprehensive coverage, systematic organization, and the bibliometric data it provides. The terms used were: "Life Cycle Engineering" alone or in combination with "Biomass" or "Biofuel" using the Boolean operator "AND"; a bibliographic search that focused only on relevant reviews of literature on the topic of "Life Cycle Assessment" was also performed for contextualization purposes; and research on an emerging topic — the production of biofuels from *Agave* — was analyzed as a case study to support the development of the steps. Filters were applied only to limit the results to documents in English and categorized as articles, literature reviews, or

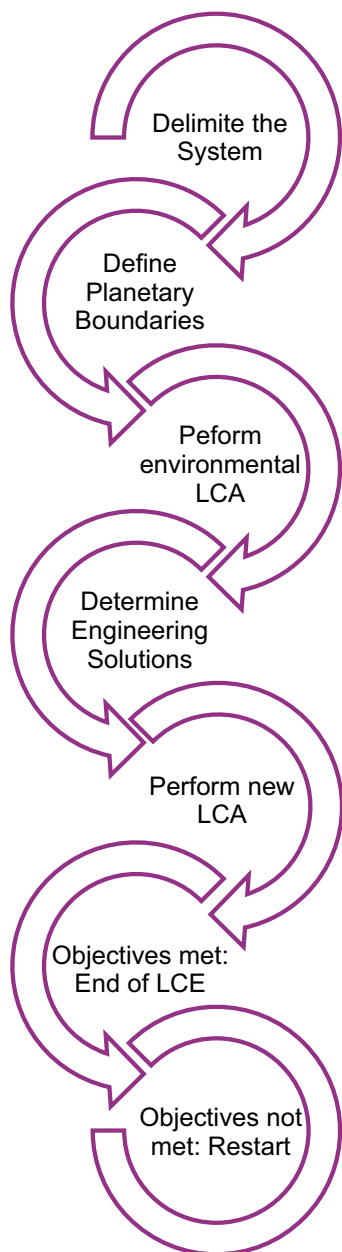
book chapters. The sequence of study was firstly to conceptualize LCE, then to analyze the existing studies in the field, thus, to examine its relationship with LCA, and then to assess the contributions related to biofuels and *Agave*.

## Results and Discussion

Life Cycle Engineering (LCE) is widely defined, in which review studies such as those by Götze and colleagues (2017) [11], Hauschild and colleagues (2020) [12], and Peças and colleagues (2016) [9] conceptualize as an approach that integrates process design with environmental, human, and economic perspectives, also working as a decision-making tool that can employ management concepts such as the Business Model CANVAS and Target Costing. Regarding Life Cycle Assessment (LCA), it is recognized as a well-established approach for analyzing environmental issues when defining processes. In addition to being standardized, it has dedicated software to apply the methodology described in the ISO standards. These features make this approach attractive for addressing the environmental dimension in LCE studies. LCA serves as the foundation for other analysis such as Life Cycle Costing (LCC, for economic aspects) and Social Life Cycle Assessment (S-LCA) [8,9] (Figure 1).

In a recent method, Kara (2023) [13] presented guidelines to be followed for application: delimiting the system to be studied, the planetary boundaries and its spatial allocation; performing an LCA to identify system elements that stand out regarding environmental impacts; determining engineering solutions with existing technologies capable of mitigating these impacts and feasible from a long-term techno-economic perspective; applying these solutions and technologies in the project; conducting a second LCA and, if objectives are not met, restarting the process. These steps are summarized in Figure 1. Among 824 documents in the English language using the keyword "life cycle engineering" in Scopus until 2025, this is the only article that provides well-defined steps for an LCE

**Figure 1.** Summary of Kara's steps of Operationalization of LCE (2019).



project or study, even though LCA is the core of these steps. The human component involved, and the techno-economic aspect are presented as the IPAT equation considering the local population, Human Development Index, and technology impact relative to the population, which may limit application by not providing clear values and references for the data used in calculations within the article.

Regarding bioprocesses, various considerations arise, since biomass derived from agriculture to be used in an industrial scale requires extensive farming system, causes biodiversity loss, generates atmospheric emissions, may raise food security issues, and the industrial process requires attention to both co-products and waste streams formation [6-8].

LCA is already widely used by practitioners as a sustainability tool in these scenarios, and a holistic study such as LCE could be applied following guidelines adaptable to different bioprocesses, encompassing LCA or other sustainability studies, especially when concerning emergent processes that lack information for such analysis. The only research found on LCE that is related to biofuels was the article by Rahman and colleagues (2023) [14], which conducted a laboratory-scale case study using microalgae as biomass. Regarding Brazil's emergent bioprocesses, although biomass production is focused on sugarcane and soy, plants capable of resisting arid climates have gained prominence and the *Agave* species were chosen as an example in the work by Honorato-Salazar and colleagues [15]. The processes of plants from the *Agave* genus were therefore used as a case study and it was noted that there are few studies in the biofuel sector. Some relevant characteristics of this genus include potential for biofuel generation due to its metabolism capable of sugar accumulation; adaptation to semi-arid regions and use in areas affected by desertification; and its cultivation involves a low technological level. Although no LCE studies exist for this biomass, 18 results were found until 2025 combining the terms "Life Cycle Assessment" and "*Agave*" on Scopus database, in which only 4 of them were related to biofuel and one were concerning *Agave sisalana* (the most produced species in Brazil), which is unrelated to the bioenergy sector [6,15].

The ethanol fuel production process based on tequila production was presented in the LCAs by Parascanu and colleagues (2021) [16], Villardi and colleagues (2024) [17] and Yan colleagues (2020) [18]. These are different studies that show that there is potential for this biomass, but further studies need

**Table 1.** LCE Framework for bioprocesses.

1. TRL	Evaluate the TRL.
2. Scenarios	Use of Project Management tools such as Proofs of Concept (POCs) and QFD Matrix (Quality Function Deployment) to help creating the desired scenarios.
3. Selection of methodologies	Develop the studies that best fits the project based on the scenarios.
4. Social Impacts	Conduct a social impact analysis, that can be a Social LCA (S-LCA) or <i>ad hoc</i> Metrics.
5. Environmental Impacts	It can be prospective LCA, Sustainability Assessments or <i>ad hoc</i> Metrics.
6. Selection of the scenario	Select the lowest-impact scenario.
7. Techno-Economic Analysis	Perform a techno-economic analysis, using Life Cycle Costing (LCC), target costing or specialized engineering software.
8. Decision	Re-evaluate the process if techno-economic feasibility is not achieved, returning to Step 2;
9. Conclusion	Final process design for scale-up.

to be conducted so the *Agave* biomasses can have similar level of importance that sugarcane, soy or corn have in the biofuel industry. Based on how these studies were conducted, the presented concept of LCE and Kara and colleagues methodology, a novel framework was developed and were summed in Table 1. It aims to adapt the existing methodology so LCE can be applied in emergent bioprocesses, despite the lack of information. Allying these steps with the exemplified LCAs or new ones can help life cycle practitioners, decision makers and stakeholders to access sustainability and define a perennial design for the bioprocess.

### Limitations

While this study provides valuable insights into Life Cycle Engineering, some limitations should be noted. The primary focus of this study was to do a critical review on how Product Development tools and Life Cycle tools can be brought together to help LCE practioners on projects that lack essential information due to novelty. Further studies are going to address a proper case study.

### Prospects

Future research may explore the comparison of life cycle impacts across different *Agave* species (e.g., tequilana, sisalana, weber), as well as sensitivity analysis to identify key inventory variables affecting the environmental performance of ethanol production. The inclusion of second-generation (2G) routes and co-product utilization (e.g., cogeneration, bioelectricity, biochar) can further refine system boundaries and improve sustainability and circularity metrics. Additional studies could assess the integration of different renewable energy sources and compare ethanol from *Agave* with other feedstocks such as sugarcane and corn using harmonized functional units and to also provide data for important metrics like RenovaCalc, which is the calculator of Brazilian's Carbon Intensity of Biofuels and can only calculate metrics for soy, sugarcane and corn.

### Conclusion

Life Cycle Engineering is a promising approach to analyze sustainability throughout a product's life

cycle. It is a tool that incorporates LCA, techno-economic analysis, and suggests including the social dimension within the assessments, thus offering a more comprehensive study. It can contribute to innovation in industry, including emerging technologies, such as the ones that have been studied in the biotechnology field. It has been illustrated by this present work the biofuel process from *Agave* as a case study, thereby supporting progress toward Sustainable Development Goals 7 and 9. It was observed that adaptations to the operational methodology of LCE could be made to better address certain concept requirements and to better accommodate projects with lower TRL that will be necessary in the bioeconomy that Brazilian Government aims to achieve.

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