XI SIINTEC
INTERNATIONAL SYMPOSIUM ON INNOVATION AND TECHNOLOGY
QUANTUM TECHNOLOGIES: The information revolution that will change the future
International Year of Quantum Science and Technology
SENAI CIMATEC UNIVERSIDADE

Proposed Life Cycle Engineering Framework for Emerging Bioprocesses

Stephanie de Melo Santana[1*], Fernando Luiz Pellegrini Pessoa[2], Hugo Gomes Damato Villardi[2], Danilo Jefferson Romero[1]
[1]*SENAI CIMATEC University, Agroindustry Department, Salvador, Bahia, Brasil*
[2] *SENAI CIMATEC University, Chemical Department, Salvador, Bahia, Brasil*
**Corresponding author: SENAI CIMATEC University; Salvador, Bahia, Brasil; sms.teca@gmail.com*

Abstract: 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.

1. Introduction

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, according to the IEA's report (International Energy Agency, 2019 [1]; Statista, 2024 [2]). The estimated production of these biofuels in 2022 was 36.89 billion liters, increasing to 42.91 billion liters in 2023 (BRAZIL, 2024a [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 (BRAZIL, 2024b [4]; BRAZIL, 2024c [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 (BRAZIL, 2024b [4]; TARDY et al., 2023 [6]). 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 and waste, 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. (LIMA, 2021 [7]; TARDY et al., 2023 [6]).

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 (BISHOP et al., 2025 [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 (PEÇAS et al, 2016 [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 (UN, 2015 [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.

2. Methodology

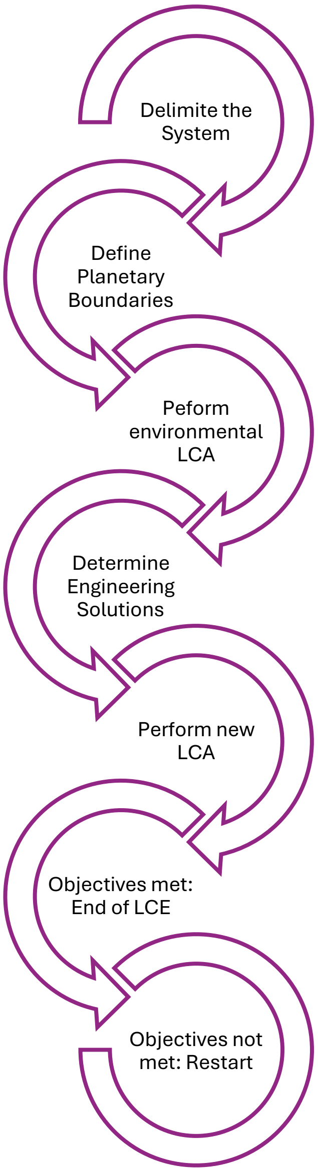
The bibliographic review was primarily conducted using the Scopus database. While additional sources such as ScienceDirect, Google Scholar, Scielo, and CAPES Periodicals were also consulted, Scopus was selected as the main source due to its comprehensive coverage, systematic organization, and the bibliometric 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.

3. Results and Discussion

Life Cycle Engineering (LCE) is widely defined, in which review studies such as those by Götze et al (2017) [11], Hauschild et al (2020) [12], and Peças et al (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). (BISHOP et al., 2025 [8];

HAUSCHILD, 2020 [12]; PEÇAS et al, 2016 [9]).

Figure 01. Summary of Kara's steps of Operationalization of LCE (2019).



Source: Adapted by the authors.

In a recent methodology, 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 01. Among 697 English-language documents using the keyword "life cycle engineering" in Scopus until 2024, this is the only article that provides well-defined steps for an LCE 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. (BISHOP et al., 2025 [8]; LIMA, 2021 [7]; TARDY et al., 2023 [6]). 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 et al. (2023), which conducted a laboratory-scale case study using microalgae as biomass. Although Brazil's production is focused on sugarcane and soy, plants capable of resisting arid climates have gained prominence and were chosen as an example in this work. (HONORATO-SALAZAR, 2021 [14]) The processes of plants from the Agave genus were therefore used as a case study and it is noted that there are few studies in the biofuel sector. Although no LCE studies exist for this biomass, 11 results were found until 2024 combining the terms "Life Cycle Assessment" and "Agave," with only 4 related to biofuel and one concerning Agave sisalana (the most produced species in Brazil), which is unrelated to this 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 (HONORATO-SALAZAR [14] et al., 2021; TARDY et al., 2023 [6]). Considering these points, the concept of LCE, and based on the fuel ethanol production process on tequila production as presented in the LCAs by Parascanu et al (2021) [15], Villardi et al (2024) [16] and Yan et al (2020) [17], Kara's methodology was adapted so LCE could be applied into low Technology Readiness Level bioprocesses, despite the lack of information and is summed in the Table 01.

Table 01. 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;
5. Environmental Impacts	• It can be prospective LCA, Sustainability Assessments or ad hoc Metrics
4. Social Impacts	• *Conduct a social impact analysis, that can be a Social LCA (S-LCA) or ad hoc Metrics*;
5. *Select the lowest-impact scenario;*	• *Select the lowest-impact scenario with Multicriteria Decision Analysis*;
6. Techno-Economic Analysis	• *Perform a techno-economic analysis, using Life Cycle Costing (LCC), target costing or specialized engineering software*;
7. Decision	• Re-evaluate the process if techno-economic feasibility is not achieved, returning to Step 2;
8. Conclusion	• *Final process design for scale-up.*

3. 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.

4. 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.

5. 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.

Acknowledgement

The authors would like to acknowledge Shell Brazil and ANP (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis) for the strategic support provided through regulatory incentives for Research, Development & Innovation. We also acknowledge EMBRAPII and Senai CIMATEC for the encouragement and funding.

References

[1] International Energy Agency. How competitive is biofuel production in Brazil and the United States? 2019. Available at: https://www.iea.org/articles/how-competitive-is-biofuel-production-in-brazil-and-the-united-states.

[2] Statista. Global biofuel production, by country 2023. 2024. Available at: https://www.statista.com/statistics/243887/biofuel-production-in-leading-countries/.

[3] Brazil. Brazil's biofuel production grows, reaching historical record. Brasília: Presidência da República, 2024. Available at: https://www.gov.br/secom/en/latest-news/2024/07/brazil2019s-biofuel-production-grows-reaching-historical-record.

[4] Brazil. Decreto Nº 12.044, de 5 de junho de 2024: Institui a Estratégia Nacional de Bioeconomia. Brasília: Presidência da República, 2024. Available at: https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/decreto/d12044.htm

[5] Brazil. Decreto Nº 12.082, de 27 de junho de 2024: Institui a Estratégia Nacional de Economia Circular. Brasília: Presidência da República, 2024. Available at: https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/decreto/d12044.htm.

[6] Tardy BL, Greca LG, Mihhels K, Lizundia E, Dumee LF, Vega LF, Integrating Arid Areas in the Global Bioeconomy:

Opportunities and Challenges toward Sustainable Biomass Generation and Management. *ACS Sustainable Chemistry & Engineering*. 2023. 11(33), 12177–12193.

[7] Lima M, Corporate Power in the Bioeconomy Transition: The Policies and Politics of Conservative Ecological Modernization in Brazil. *Sustainability*. 2021. 13(12), 6952.

[8] Bishop G, Girón-Domínguez C, Gaffey J, Henchion M, Fealy R, Zimmermann J, Kargupta W, Styles D, A life cycle thinking-based environmental risk framework for screening sustainable feedstocks in early-stage bioeconomy projects. Resources, Environment and Sustainability. 2025. 20, 100201.

[9] Peças P, Götze U, Henriques E, Ribeiro I, Schmidt A, Symmank C, Life Cycle Engineering – Taxonomy and State-of-the-art. *Procedia CIRP*. 2016. 48, 73-78.

[10] UN. *Objetivos do Desenvolvimento Sustentável.* Brasília: Nações Unidas - Brasil, 2015. Available at: https://brasil.un.org/pt-br/sdgs. Access: 08/01/ 2025.

[11] Götze U, Peças P, Schmidt A, Symmank C, Henriques E, Ribeiro I, Schüller M, Life Cycle Engineering and Management – Fostering the Management-orientation of Life Cycle Engineering Activities. *Procedia CIRP*. 2017. 61, 134–139.

[12] Hauschild MZ, KARA S, RØPKE I, Absolute sustainability: Challenges to life cycle engineering. *CIRP Annals - Manufacturing Technology*. 2020. 69, 533-553.

[13] Kara S, Herrmann, Operationalization of life cycle engineering. *Resources, Conservation & Recycling*. 2023. 190, 106836.

[14] Honorato-Salazar JA, Aburto J, Amezcua-Allieri MA, Agave and Opuntia Species as Sustainable Feedstocks for Bioenergy and Byproducts. *Sustainability*. 2021. 13(21), 12263.

[15] Parascanu MM, Nestor Sanchez N, Sandoval-Salas F, Carreto CM, Soreanu G, Sanchez-Silva L, Environmental and economic analysis of bioethanol production from sugarcane molasses and agave juice. *Environmental Science and Pollution Research*. 2021. 28, 64374–64393.

[16] Villardi HGD, Cruz AI, Cruz VF, Junior ARM, Azzoni S, Pessoa FLP, Simulation of an Agave Plant for Ethanol Production. X Simpósio Internacional de Inovação e Tecnologia, Blucher Engineering Proceedings [Internet]. 2024 11;1-10.

[17] Yan X, Tan DKY, Inderwildi OR, Smith JAC, King DA, Life cycle energy and greenhouse gas analysis for agave-derived bioethanol. *Energy & Environmental Science*. 2011. 4(9), 3110–3121.