

Life Cycle Assessment of an innovative polyhydroxyalkanoates biorefinery: addressing background data gaps for sustainable development

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Abstract:

The synthesis of polyhydroxyalkanoates (PHAs) from waste feedstock has gained increasingly relevance as it appears to be a more economical and sustainable way of production. In this context, the Horizon Europe project BioLaMer proposes to use the food eating black soldier fly larvae as the fermentation medium. To ensure the environmental sustainability of BioLaMer proof-of-principle, Life Cycle Assessment is performed since its beginning. Currently, Life Cycle Inventory is under development and some of the typical challenges when working with innovative processes are encountered. Among them, the lack of background data is particularly important. Here, the solution comprising the modelling of the missing datasets on LCA software will be proposed as the most appropriate one for innovative processes.

1. Polyhydroxyalkanoates

Polyhydroxyalkanoates (PHAs) are natural polyesters accumulated by various microorganisms as a source of energy and carbon storage (Anderson and Dawes, 1990). These biopolymers exhibit physical and mechanical properties similar to conventional plastics like polyethylene and polypropylene (Ciesielski et al., 2015). Consequently, PHAs are gaining significant attention as a more sustainable alternative to conventional plastic due to their inherent biodegradability, biocompatibility, and renewability (Ciesielski et al., 2015). However, large-scale PHA production remains limited due to high production costs, estimated to be five times greater than their petrochemical counterparts (Cristóbal et al., 2016). Utilizing waste streams like wastewater sludge or food waste as feedstock for PHA production can offer a more economical and sustainable solution (Battista et al., 2021; Chen and Patel, 2012). Therefore, research efforts are in place aiming at the optimization of the fermentation strategies and downstream processing techniques for waste feedstocks (Pagliano et al., 2021).

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1.1 Environmental sustainability of PHA production: a brief overview

Life Cycle Assessment (LCA) studies play a crucial role in assessing the environmental impact of PHAs' production. Its early application helps to ensure the implementation of sustainable solutions in the value chain and to avoid the risk of environmental burden shifting. Various LCA studies have been published through the years on the topic, indicating that all phases of PHAs production must be optimized from both an economic and an environmental perspective for them to be a viable alternative to conventional plastic (Vicente et al., 2023).

The feedstock selection and processing stage significantly influences the performances of PHA production (Dietrich et al., 2017; Jiang et al., 2016). Agricultural crops and waste streams are the two primary feedstock sources. However, while purpose-grown crops are readily available, they can lead to high environmental burdens in areas like eutrophication and human toxicity (Cristóbal et al., 2016). Emerging research explores using alternative carbon sources like food waste or wastewater sludge (Samorì et al., 2019; Yadav et al., 2020). This approach not only reduces reliance on virgin materials but also addresses waste management challenges (De Donno Novelli et al., 2021).

Great heterogeneity can be found in published literature in relation to PHA production process (Cristóbal et al., 2016). Regarding fermentation, fed-batch processes demonstrated lower environmental impact and cost compared to batch processes due to reduced energy demand (Lopez-Arenas et al., 2017). Another aspect that influences both the environmental impacts and the cost-benefits of the process is the microbial culture, that can be pure or mixed. In recent years mixed cultures are gaining traction due to their ability to utilize waste streams as feedstock (Nielsen et al., 2017) and eliminate the need for sterile conditions (Gurieff and Lant, 2007).

For the downstream PHA extraction and purification stages, further research is required to optimize processes and minimize environmental impact. Current methods often involve physical separation, pre-treatment, and extraction using hazardous solvents, which contributes significantly to the high energy consumption and environmental impact of the process (Kosseva and Rusbandi, 2018). Saavedra del Oso et al. (2021) compared various downstream processing alternatives. Mechanical disruption appears favorable for its environmental performance, while surfactants hold promise for low-grade purification. Chemical digestion offers high-purity PHA but requires optimization for solvent recovery. Solvent extraction remains relevant for demanding purity needs, but necessitates efficient solvent recycling.

2. An innovative feedstock for PHA production: the BioLaMer project

Selecting sustainable feedstocks, such as waste streams, offers a promising approach to mitigating the environmental burden and fostering a more circular bioeconomy. On these premises, the BioLaMer Horizon Europe project aims to demonstrate a proof-of-principle innovative biorefinery to produce two biopolymers: PHAs and chitosan. Its element of innovation lays in the employment of a new carbon-rich feedstock: the black soldier fly larvae (*Hermetia illucens*). These food-eating insects appear to be an high impact feedstock for cost-effective PHAs production due to their chemical invariability, which allows to reduce the need of pre-treatment before the bioreactor step. Moreover, as the primary source of nutrition used in the project for larvae feeding is food waste, their use as the carbon-rich source for PHA production allow to simultaneously address the problem of food waste management.

With this line of work, life cycle thinking (LCT) appears of primary importance and both Life Cycle Assessment and Life Cycle Costing are being performed. In particular, University of Bologna is responsible for the environmental analysis and AquaInSilico is leading the economical evaluations of the BioLaMer system. The primary aim of the sustainability work package is to ensure the minimizations of the impacts associated with this production route. Therefore, in order to ensure both the environmental and the economical viability of this proof-of-principle, LCA and LCC have been performed since the very early-stages of the project. BioLaMer started in April

2023, and after the goal and scope definition, the Life Cycle Inventory (LCI) is now under development.

3. A Life Cycle Inventory challenge for innovative processes: the lack of background data

A thorough LCI is the foundation for robust LCA and LCC results. A LCI that is as accurate as possible is especially important when working with early-stages innovative processes, as the BioLaMer one. Data referred to single-operation unit processes and the minimization of black-boxes not only enhances transparency and reduces potential multifunctionality issues but also allows to have the required flexibility so that it have the ability to be adapted to the changes that will likely occur as the project itself advance. This possibility is closely related to how its construction process have been carried out. Furthermore, a detailed qualitative LCI serves as a critical foundation for the upscaling process, facilitating the transition from lab-scale processes to pilot plants.

However, LCI of innovative processes often also poses substantial challenges to solve: lack of foreground and background data, poor data reliability, difficulty in the estimation of real-scale quantities. One of the most frequent one is the lack of background process data. BioLaMer makes no exception, and several chemicals used in the project secondary data are missing. In this case, three reagents are missing in our LCA database: the sodium molybdate, the cobalt II chloride hexahydrate and the dipotassium phosphate. These chemicals find application during the bioreactor stage of the production process. In association with others, they aim at the optimization of the environmental condition for bacterial growth

This lack of background data issue can be overcome with various strategies, each with its advantages and drawbacks. Among them, a frequent strategy is the use of proxies, which comprises the use of available datasets of substances similar to the missing one. Other approaches comprise a literature review and expert consultation, both of which can provide valuable insights into the environmental and economic burdens associated with the processes or materials under investigation and help bridge the data gap with informed approximations. Lastly, modelling and simulations can be a valuable tool to estimate environmental and economic impacts for the missing data. Of all the above approaches, the latter is the one that we will apply to the BioLaMer project, as is the solution that -in this case- maximizes the chances of an accurate impact assessment. This is because modelling the production of the chemical of interest allows the LCA and LCC analysts to have more control over what is included and excluded from the study, leading to more transparent data. Moreover, having control over the model of the life cycle of the reagents' supply chain enables to change it in accordance with the scope of the study which can be modified, as the project advance, for example from lab-scale to a pilot one.

The method that we are applying is based on the modelling of the chemical's synthesis in LCA for Experts. To do so, at first, information regarding the stoichiometric reaction, along with the selectivity, conversion and yield of the reaction are sought in published patents or in chemical encyclopaedias, as the Ullman one (Hischier et al., 2005; Ullmann, 2003). Then, the minimum energy consumption needed for the reaction to take place, is determined based on the molar enthalpy change derived from the physical and chemical parameters of the involved reagents and on its reaction temperature (Andraos, 2016).

3. Conclusions

PHAs possess considerable potential as a sustainable alternative to conventional plastics. Addressing the economic challenges associated with large-scale production through the utilization of waste streams and the optimization of processes is crucial for their widespread adoption. Life cycle thinking, implemented in the BioLaMer project through LCA and LCC analysis, play a vital role in understanding the environmental and economical implications of polyhydroxyalkanoates (PHAs) production. These assessments help identifying areas for improvement and promoting sustainable practices in bioplastic manufacturing. In this context, the

BioLaMer project aims to valorise waste streams producing biopolymers and added-value bioplastic products through an innovative biorefinery process, which uses the food eating black soldier fly larvae as the fermentation medium. To ensure the overall sustainability of the process, LCA and LCC are performed since its early-stages. At the moment, its LCI is under development. Along with all the advantages of early environmental evaluation of innovative processes, this also brings some challenges. Among them, one of the most common one during the LCI phase is the lack of background data. This can be overcome by implementing various strategies, from the use of proxies to literature research. On the matter, a particularly appropriate solution for innovative processes is the modelling of the missing datasets on LCA software, which ensure the most precise and transparent representation of the production chain, leading to more robust impact assessment results.

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