Preliminary optimization of the environmental performance of PHA downstream processing

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Abstract

As downstream processing has been identified as a bottleneck for the sustainable development of the polyhydroxyalkanoates (PHAs) value chains, this work aims to provide new insights for the optimization of its environmental performance. After identifying the most promising methods for PHA recovery and purification, four processes with two different system functions,high- and low-grade PHA, were defined and scaled up. The environmental performance of these processes was evaluated by life cycle assessment (LCA). Processes based on solvent extraction showed a worse environmental performance due to the high energy requirements of solvents recovery. Processes relying on chemical digestion showed a better environmental performance when combined with other technologies such as high pressure homogenization, which allows a reduction of the amount of chemicals employed. Therefore, two main improvement actions were proposed to overcome these hotspots and estimate the environmental burdens reduction: heat integration in larger facilities would reduce the heat duty, while introducing a chemical recovery unit or combining chemical digestion with other technologies would reduce those impacts related to chemicals consumption. Through this work, it is demonstrated that the environmental performance of PHA downstream processing can be improved if the process design include life cycle assessment from its conception.

Keywords: Biobased materials, Polyhydroxyalkanoate extraction, Process optimisation, Life cycle assessment.

1. Introduction

PHAs still have a reduced market share due to their high production cost, 2.2 to 5 €·kg^{-1}, compared to less than 1 €·kg^{-1} for oil-based plastic, (Sabapathy et al. 2020). Furthermore, studies based on life cycle assessment (LCA) have reported considerable environmental impacts due to high energy requirement in the bioplastic value chain, especially during the PHA production and downstream processing (Dietrich et al. 2017; Heimersson et al. 2014). The use of great amounts of chemicals and high energy requirements pinpoints to the PHA downstream processing as an economic and environmental hotspot, being able to account for up to 50% of the production costs (Pérez-Rivero et al. 2019). However, a lack of individualized LCA on PHA downstream processing was detected. Therefore, the objective of this work is to provide insights on PHA downstream optimization by focusing on its environmental performance and hotspots analysis.

2. Life cycle assessment of the selected PHA downstream processes

2.1. Scenarios definition and process design

A systemic review of the state-of-the-art was carried out to identify the most promising methods for PHA recovery and purification, and set the goal & scope of the current study. Process definition and design was supported on articles, patents and process simulation. A summary of the selected processes background, recovery technology employed, scale and their technology readiness level (TRL) is showed in Table 1.

Table 1. Processes definition of PHA downstream processes, accounting their quality grade, substrate, type of culture, recovery method, TRL.

Grade	Feedstock	Culture	Recovery method	Scale (t/year)	TRL
H1	Glucose	Pure	Acetone extraction	10,000	9
H2	Food industry byproducts	Pure	HPH + SDS digestion	10,000	9
L1	Canning industry waste	Halophilic bacteria	Osmotic shock + SDS digestion	1,500	4
L2	Sugar molasses byproducts	Pure	Fusel alcohols extraction	100,000	8

2.2. Goal & scope and life cycle inventory

Two functional units were defined as the system function to be covered is not equivalent, i.e. two quality grades namely, 1 kg of high-grade PHA and 1kg of low-grade PHA. The system boundaries followed a gate-to-gate approach in both system functions, covering from the PHA enriched biomass to the purified powder.

With regards to life cycle inventory construction, mass and energy balances from process design were employed for primary data while Ecoinvent v.3 database was employed for secondary data. The impact assessment followed a midpoint approach, being global warming potential (GWP IPCC 2016), human toxicity and fossil depletion (Hierarchist ReCiPe(H) v1.13) the selected impact categories. To do so, SimaPro software v8.3 (PRé Sustainability, NL) was used.

2.3. Results of life cycle impact assessment

Processes based on solvent extraction (H1 & L2) are less recommended from an environmental perspective due to the high energy requirements of solvents recovery. The performance of process L2 is likely to be better than reported in Figure 1, as there was no available data to fusel alcohols production from biomass and thus, isoamyl alcohol chemical based was employed in the life cycle inventory construction. Processes H2 and L1 show a better environmental profile, especially in global warming potential and fossil depletion, as result of combining chemical digestion with high pressure disruption and osmotic shock respectively, lowering the amount of chemicals employed. However, process L1 is highly energy intensive, and alternatives such as heat integration should be considered.

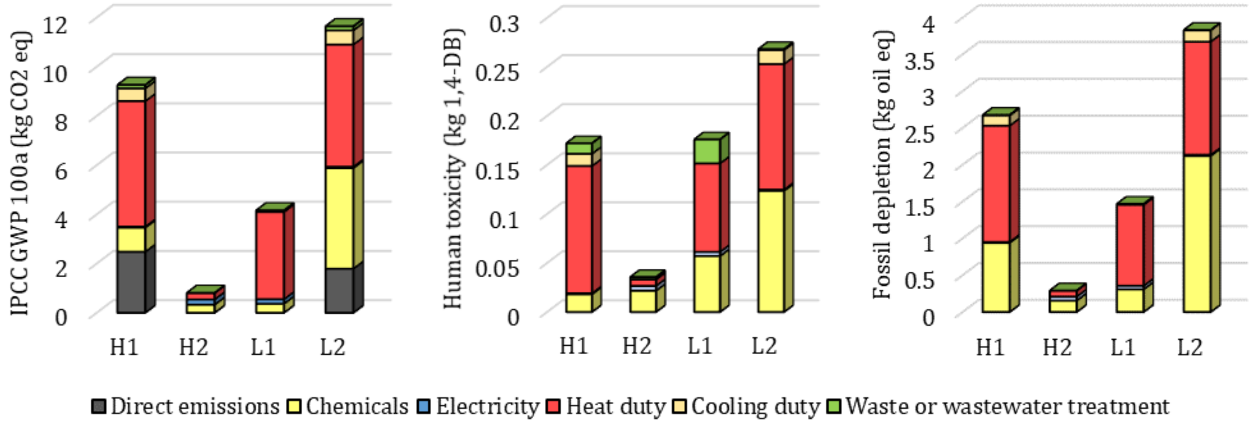

Figure 1. Results from characterization and life cycle costing of high-grade (H1 & H2) and low-grade (L1 & L2) processes. AD: annual depreciation; U: utilities; m: materials; L: labour; M: maintenance.

3. Optimization of the PHA downstream processes environmental performance

Life cycle impact assessment and sensitivity analysis highlighted the impact of heat and chemical consumption in the process environmental performance. Energy source has a great importance on environmental impacts, e.g. H1 environmental impacts would be reduced up to 60% in human toxicity if natural gas was employed as heat source. Likewise, H2 environmental impacts would be reduced up to an average 20% by providing electricity from a low carbon footprint mix, here represented by the Swedish electricity mix based on renewable energies, was chosen as electricity source. As heat source is the main contributor to processes L1 and L2 environmental impacts, heat integration is proposed for lowering them (Table 2), especially considering that both processes are integrated in a canning industry and a molasses biorefinery respectively. Sensitivity analysis also shows that the incorporation of a chemicals recovery unit should be considered if chemical digestion is employed, i.e. environmental impacts could be doubled if chemicals recovery unit is not used.

Table 2. Results of improvement actions proposed to optimize the environmental performance of L1 and L2 processes.

Process	Hotspot	Framework	Improvement actions	Environmental impacts reduction		
				GWP	Human toxicity	Fossil depletion
L1	Heat duty	Canning industry waste	Heat integration	83%	50%	73%
L2		Sugar molasses byproducts		12%	13%	11%

4. Conclusions

This work provides preliminary insights on the potential to optimize the environmental performance of PHA downstream processes from an early stage design. Some conclusions were extracted from the life cycle assessment:

- Processes based on solvent extraction require high amounts of energy, and thus, low carbon heat sources and heat integration in larger facilities must be considered to reduce environmental impacts.
- Chemical digestion shows a better environmental performance when is combined with mechanical digestion or osmotic shock. The addition of a chemicals recovery unit should be considered.
- High pressure homogenisation is the most promising method, while employing a low carbon electricity mix could reduce its environmental impacts.

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