Techno-economic and environmental sustainability assessment of Poly (butylene succinate) production process from sugar beet pulp through biorefinery development

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Introduction

The transition towards a bio-based economy renders the utilisation of crude renewable resources for the production of bio-based chemicals, polymers and materials imperative. The sustainable production of such bio-based products requires the development and implementation of innovative biorefinery concepts. Poly(butylene succinate) (PBS) is a biodegradable polyester synthesized through polycondensation of bio-based succinic acid and 1-4-butanediol. It is a very promising biopolymer because its mechanical properties are comparable with those of widely used fossil-derived plastics. Both building blocks are produced via fermentation process using the renewable feedstock sugar beet pulp. Sugar beet pulp (SBP) is a promising industrial side stream from the sugar production industry, suitable for biorefinery development due to its geographical distribution in EU-28 countries, its high carbohydrate as well as high pectin contents. Pectin is a high added value co-product that can be exploited after its extraction of sugar beet pulp. Therefore, this work focuses on process design, techno-economic evaluation and environmental assessment of PBS production process using sugar beet pulp as feedstock.

Experimental

The first step for the techno-economic assessment of the PBS production process as well as the environmental performance evaluation is the process design in appropriate software (e.g. UniSim, Aspen). The fermentation efficiency of succinic acid and 1,4-butanediol, their downstream separation and purification process as well as the polymerization reaction conditions are selected by identifying relevant literature-cited publications (Ma et al., 2011, Burgard et al., 2016, Kamikawa et al., 2012). Techno-economic evaluation is based on preliminary economic analysis (accuracy up to ± 30%) that is carried out for the estimation of the fixed capital investment and the operating costs. The methodology for the estimation of fixed capital investment (FCI) required to construct the plant and the cost of manufacture (COM) is implemented following well-known procedures and rules of thumb and these metric are calculated for various plant capacities (Peters and Timmerhaus, 2003; Turton et al., 2018). Based on FCI and COM, a discounted cash flow (DCF) analysis is carried out, in order to estimate the minimum selling price (MSP) of the process, by determining the market price of the product where the NPV is zero at the end of plant life time. Moreover the discounted payback period (DPP) as well as the optimum plant capacity (OPC) for the investment plant are defined. As regards the environmental performance, a Life Cycle Assessment (LCA) is performed using the GaBi software and common LCA methodology (ReCiPe 1.08) for the analysis. The system boundaries for the analysis is "cradle to gate" and the functional unit is 1 kg of produced PBS. Finally, the environmental externalities, e.g. the quantifiable costs that occur from the monetization of environmental impacts of the process, are estimated and taken into consideration along with the economic cost. By determining the final life cycle cost, having included the externalities, the production of bio-based products could be comparable to their conventional counterparts which are derived from fossil raw materials.

Results and Discussion

The economic metrics, which are estimated in various plant capacities, are FCI, COM, MSP and DPP. These metrics are presented per kilogram of PBS (Table 1) in the optimum plant capacity (OPC), the capacity after which the COM or MSP reach a plateau and thus remain constant, that is 58,630 t_{PBS}/y. Since SBP is employed as feedstock, the revenue from crude pectin extract sales as co-product is also taken into consideration (price: 4 $/$kg_{pectin}$) along with the revenue from the sales of the main product (price: 4.00 $/$kg_{PBS}$) It has been assumed that no further processing for the crude pectin extract is required, although, in reality, modification of the crude pectin extract may be needed depending on the final application of pectin. As regards the environmental performance, various environmental metrics are determined according to the methodology followed for the estimation of the externality costs (de Bruyn et al., 2018). The final cost of externalities for PBS production from SBP accounts for 0.35 $/$kg_{PBS}$. The final life cycle is the sum of the minimum selling price and the externality cost. This cost is compared to the life cycle cost of the fossil-derived counterpart of PBS that is considered to be the general purpose polystyrene (GPPS). The life cycle cost of the fossil polymer is the sum of its current market (1.72 $/$kg_{GPPS}$) and the estimated externality cost (0.32 $/$kg_{GPPS}$). As Figure 1 illustrates, the life cycle cost of SBP-derived PBS is 13% lower that the life cycle cost of GPPS.

Table 1. Metrics of techno-economic evaluation for PBS production process in the optimum plant capacity.

Metrics	Value ($\$/kg_{PBS}$)
Fixed Capital Investment (FCI)	5.53
Cost of Manufacture (COM)	3.88
Minimum Selling Price (MSP)	1.37
Discounted Payback Period (DPP)	6

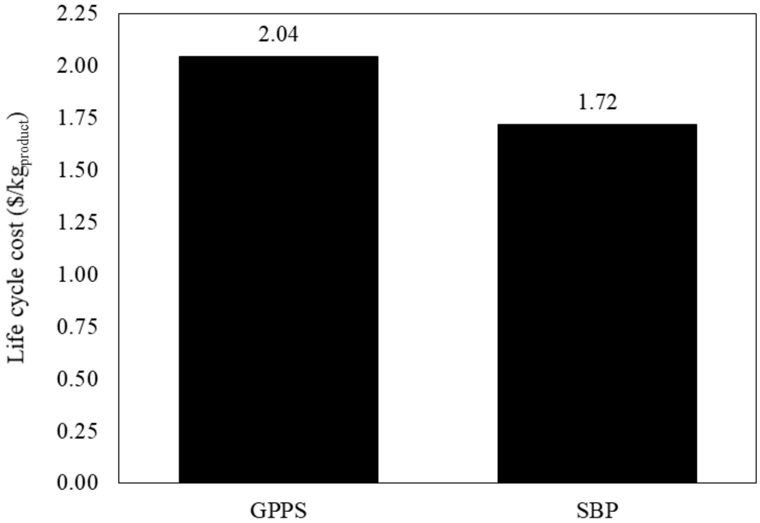

Figure 1. Life cycle cost of bio-based PBS and its fossil-based counterpart GPPS.

Conclusions

Sugar beet pulp is a promising feedstock not only because of its high carbohydrate content and geographical distribution but also because of its high pectin content. Pectin can be an important co–product and its valorisation can improve significantly the profitability of the whole biorefinery concept. Poly(butylene succinate) (PBS) production process is evaluated through economic and environmental perspective. Important metrics from both pillars are estimated and the results are combined in order to calculate the final life cycle cost of the PBS production. Comparison with the fossil counterpart of PBS points out that the bio-based polymer indicates better performance if SBP is employed as feedstock and environmental externalities are taken into consideration.

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References

1. J. Ma, M. Jiang, K. Chen, B. Xu, S. Liu, P. Wei, H. Ying, H. Chang, P. Ouang, *Bioprocess Biosyst. Eng*., **34 (4)** 411–418 (2011).
2. A. Burgard, M.J. Burk, R. Osterhout, S. van Dien, H. Yim, *Curr. Opin. Biotechnol.*. **42** 118–125 (2016).
3. M. Kamikawa, T. Matsuo, K. Oka, T. Kondo, Y. Sase, M. Tanto, *United States Patent* (2012).
4. M.S. Peters, K.D. Timmerhaus, R.E. West, *McGraw-Hill*, 5th ed. (2003).
5. R. Turton, R.C. Baile, W.B. Whiting, J.A. Shaeiwitz, D. Bhattacharyya, *Prentice Hall*, 5th ed., New Jersey (2018).
6. S. de Bruyn, M. Bijleveld, L. de Graaff, E. Schep, A. Schroten, , R. Vergeer, S. Ahdour, *CE Delft report* (2018).