Economic and Environmental Evaluation of Poly(3-Hydroxybutyrate) Production Utilizing Brewery Spent Grain and Implementing Biological Recirculation of the Biopolymer

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Introduction

This study presents a holistic sustainability assessment of poly(3-hydroxybutyrate) (PHB) production, specifically tailored for food packaging applications. The innovative approach involves utilizing brewery spent grain hydrolysate and PHB biological recycling-derived monomers as fermentation feedstock, effectively closing the loop in the production cycle. To gauge the environmental and economic implications comprehensively, we conducted a dual evaluation through Life Cycle Assessment (LCA) and Techno-Economic Evaluation (TEA). The bioprocess is strategically designed for seamless integration into the brewery industry, with the overarching goal of bolstering the sector's sustainability. By harnessing the circularity of the biopolymer, wherein degradation monomers serve as carbon sources in microbial fermentations, we optimize feedstock availability and minimize resource waste. Innovative technology of dielectric barrier discharge (DBD) atmospheric cold plasma (ACP) was used on the brewery spent grain (BSG) pretreated to enhance the performances of the followed enzymatic hydrolysis. In the downstream separation purification process (DSP), environmentally friendly green solvents were employed for the extraction of intracellular PHB. The outcomes of our LCA and TEA analyses serve as crucial guides, enabling the identification of process hotspots and pinpointing areas for targeted improvements. By addressing these identified areas, the environmental impact and production costs can be effectively reduced, thereby advancing the sustainability profile of PHB production for food packaging applications.

Materials & methods

Process design was conducted using UniSim software from Honeywell. The design initiates with the preparation of feedstocks, with the first involving the pretreatment of brewery by-products using DBD atmospheric cold plasma, followed by enzymatic hydrolysis. The second feedstock is derived from the degradation of biopolymers into their respective monomers. The process then progresses to the fermentation stage and DSP using eco-friendly solvents such as 1,3-dioxolane, dimethyl carbonate, and anisole. All design parameters, including processing conditions, extraction yields, pretreatment and hydrolysis yields, fermentation efficiency, and material balances, were determined based on experimental results. Techno-economic evaluation is based on preliminary economic analysis (accuracy up to ± 30%). The methodology for the estimation of fixed capital investment (FCI) required to construct the plant and the cost of manufacture (COM) in different plant capacities is implemented following well-known chemical engineering procedures and rules of thumb [1,2]. A discounted cash flow (DCF) analysis has been carried out to estimate the minimum selling price (MSP) of PHB considering the proposed sustainable bioprocess as well as conventional methods for BSG pretreatment using sodium hydroxide and PHB purification using sodium hypochlorite and chloroform. Moreover, the optimal plant capacity (OPC), the discounted payback period (DPP) and the Net Present Value (NPV) have been estimated. Life Cycle Assessment (LCA) is performed using the GaBi software and the LCA methodology CML 2001 (Jan. 2016). The system boundaries for the analysis characterized as "cradle to gate" and the functional unit is 1 kg of produced PHB.

Results & discussion

The operational capacity (OPC) for PHB production using the proposed bioprocess was projected at 15 kt/year, with a corresponding fixed capital investment (FCI) estimated at $39 million. Various scenarios were explored to assess the cost of manufacturing (COM) and market selling price (MSP) of PHB, incorporating different green solvents for PHB purification. The COM per kg PHB ranged from $2.6 to $3.8/kg, while the MSP fell between $3.3 and $4.9/kg. In terms of environmental impact, the Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP fossil) of PHB production from brewery by-products using the proposed bioprocess were determined to be 1.17 kg CO_2-eq per kg PHB and 35 MJ per kg PHB, respectively.

Conclusions

This study provides a techno-economic evaluation and life cycle assessment of an innovative bioprocess for poly(3-hydroxybutyrate) (PHB) production, utilizing brewery spent grain (BSG) and its derived monomers as key components. The MSP of PHB ($3.1-3.9/kg) was lower than the current PHB market price ($6.5/kg) [3]. The estimated GWP (1.47 kg CO^2-eq per kg PHB) and ADP fossil (35 MJ per kg PHB) were lower than the respective values of fossil derived counterparts. The bioconversion of brewery industry by-products into poly(3-hydroxybutyrate) (PHB), with a focus on the circularity perspectives of the material, holds the potential to establish a sustainable and novel bioprocess.

References

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