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Case Study

Economic and environmental assessment of propionic acid production by fermentation using different renewable raw materials

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HIGHLIGHTS

- A process design for production and recovery of bio-based propionic acid.
- Renewable energy sources in production needed to reach reduction of GWP.
- Assessment highlights need for higher space–time yields to reach economic viability.

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ABSTRACT

Production of propionic acid by fermentation of glycerol as a renewable resource has been suggested as a means for developing an environmentally-friendly route for this commodity chemical. However, in order to quantify the environmental benefits, life cycle assessment of the production, including raw materials, fermentation, upstream and downstream processing is required. The economic viability of the process also needs to be analysed to make sure that any environmental savings can be realised. In this study an environmental and economic assessment from cradle-to-gate has been conducted. The study highlights the need for a highly efficient bioprocess in terms of product titre (more than 100 g/L and productivity more than 2 g/(L·h)) in order to be sustainable. The importance of the raw materials and energy production for operating the process to minimize emissions of greenhouse gases is also shown.

1. Introduction

Production of propionic acid (PRA) from fermentation of glycerol is a promising development target since glycerol is obtained in large quantities as a by-product from biodiesel production. The annual global production of propionic acid is mainly covered by conversion of fossil resources at approximately 350,000 tonnes per year. It is mainly used as preservative in food and feed and in the herbicides and polymer industries (Sauer et al., 2008) and is sold at a market price of about 1–2 €/kg. Production of propionic acid by fermentation has been reported by a number of groups (Liu et al., 2012a).

Most environmental systems studies on renewable chemical production investigate systems where dedicated crops, such as corn or sugarcane, are used as feedstock (Pietrini et al., 2007). Using by-products from agricultural or industrial processes has been identified as a promising way to reduce the competition for arable land (Berndes et al., 2011) and their use as feedstocks for production of biofuels is being promoted in Europe through the Renewable Energy Directive (European Commission, 2009). The use of by-products can also significantly reduce the cost of raw materials, which usually comprise a significant part of production cost. In the EU, the production of rapeseed oil-based biodiesel (RME) has led to an increase in the production of glycerol, a by-product from the production of RME, which initially resulted in bio-glycerol replacing conventional, fossil-based glycerol. However, this market is becoming saturated and therefore new value adding uses for glycerol would be desirable. One option would be to use it as substrate in industrial fermentation processes for production of biobased chemicals (Yazdani and Gonzales, 2007).

Also alternative raw materials could be considered for propionic acid production, for example other by-products from agriculture and industry as well as dedicated crops. Hydrolysed sugarcane molasses has previously been used successfully as raw material for propionic acid (PRA) production (Feng et al., 2011). Not only the carbon source, but also the source of nitrogen for the fermentation has a potential impact on the cost and environmental performance. Replacement of yeast extract which is an expensive nitrogen source with a low cost, available by-product such as

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potato juice could reduce raw material costs. Potato juice is a by-product of extraction of starch from potato, which presently goes to waste or is used as fertilizer.

The major driving forces for developing production of biobased chemicals in general are the depleting fossil oil resources and the concerns about climate change. However, the actual environmental advantages of biobased fuels and chemicals have been questioned, especially those derived from crops where the cultivation may cause either direct or indirect land-use changes (Searchinger et al., 2008). Apart from its obvious influence on the product cost, the production process may also have a significant environmental impact. This is particularly true if the process efficiency is low, energy intensive unit operations are necessary (e.g., distillation), or fossil fuels are used to generate process energy (Tufvesson et al., 2013). Several investigations of the environmental effects of renewable chemicals have been performed, in particular of bio-based ethanol, showing both positive and negative results (Börjesson, 2009). In addition to this, many biobased processes struggle to be cost competitive as compared to fossil based chemicals. Still, very few studies have reported on the economy of the process although cost competitiveness is a prerequisite for implementation. Moreover, carrying out both economic and environmental assessments in early stages of process development is essential in order to direct efforts and set targets so that a cost efficient as well as environmentally benign process will be developed. Methods for a full cost assessment are extensive and require detailed information on raw material costs, equipment and location of the site. However, cost estimates should be made also in the conceptual stages of a project even when comprehensive specifications (or other data) are not available (Tufvesson et al., 2011).

Many parameters interact to determine economic feasibility as well as the environmental impact and many of these parameters influence both. This article aims to identify the critical process parameters and to investigate the impact of these for the production of propionic acid on both the environmental impact, with focus on greenhouse gas performance, as well as the production costs. The basis of this paper is a recent publication by Dishisha et al. (2013) which describes a process with comparably high productivities and PRA titers. The process investigated in this paper was not operated in commercial scale. Thus, the economic comparison is based on estimations and simplified profitability measures. This study considers different scenarios for raw material use as well as different designs for recovery of the product down-stream of fermentation.

2. Methods

2.1. Environmental assessment methodology

The life cycle assessment (LCA) performed in the present paper was carried out according to the methodology standards described in ISO 14044 (ISO, 2006). The functional unit was set to 1 tonne of propionic acid at the factory gate. The LCA was limited to emissions of greenhouse gases expressed as Global Warming Potential (GWP) in a 100 year perspective and measured as CO_2-equivalents.

Life cycle inventory data were obtained by literature studies and through the Ecoinvent database (Ecoinvent Centre, 2009). Economic allocation was applied to account for by-products throughout the study. To provide the most realistic basis for comparison economic allocation was chosen since the products included are of different character. Fig. 1 illustrates the investigated production system for production of the functional unit.

Energy consumption in the process steps was according to Patel et al. (2006). Natural gas was used for production of steam and electricity in the base case. Energy input data are shown in Table 1.

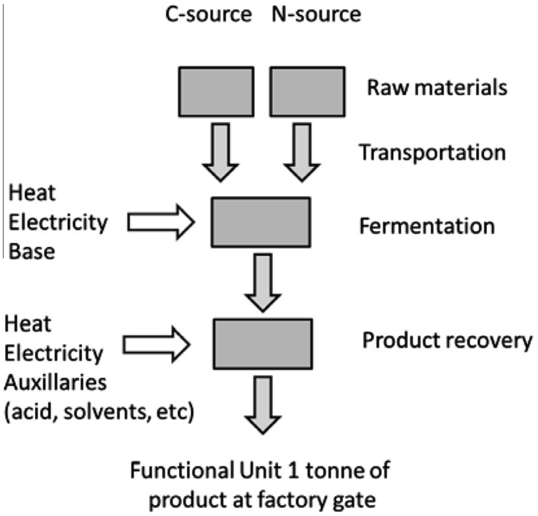

Fig. 1. Description of the overall production system for propionic acid by fermentation.

The importance of using less carbon intensive energy such as wood chips for production of steam and Swedish average electricity was considered in the sensitivity analysis.

The environmental impact of biobased propionic acid was compared with fossil-based propionic acid that was assessed by Ekman and Börjesson (2011).

2.2. Process economics

Process cost can be divided into two categories: capital investment (CapEx) and operating cost (OpEx). CapEx represents the one-time expense for the design, construction, and start-up of a new plant, including installation with all the accessories needed for start-up and operation (Tufvesson et al., 2011). OpEx includes the running cost of, for example, raw materials, utilities, waste management and operating labour (direct as well as overhead costs). The basis for the capital estimate is equipment cost data. Based on this information the total capital investment can be calculated through the application of multipliers, such as the Lang factor. In this study a Lang factor of 5 was assumed (Peters and Timmerhaus, 1990).

The software SuperPro Designer (Intelligen, Scotch Plains. NJ) was used to size the equipment and estimate the cost of all items except the fermentor which was set to a volume of 200 m^3 and cost based on estimates from a web based database (www.matche.com). The costs were subsequently transferred to an excel spread sheet where the final calculations were made. To calculate the annual capital cost (depreciation cost) or cost per unit of product, the investment cost was converted to an equivalent annual

Table 1
Energy data used in the calculations.

		Primary Energy factor	GWP	Reference
Process heat	Natural gas	1.05	60.3 kg CO_2-eq./GJ	Gode et al. (2011)
	Wood chips	1.05	10 kg CO_2-eq./GJ	Lindholm et al. (2010)
	Hard coal	1.1	106.7 CO_2-eq./GJ	Gode et al. (2011)
Electricity	Natural gas-based	2.1	474 g CO_2-eq./kWh	Gode et al. (2011)
	Swedish average	2.1	36.4 g CO_2-eq./kWh	Gode et al. (2011)