Bioresource Technology 198 (2015) 673–681

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Economic analysis and environmental impact assessment of three different fermentation processes for fructooligosaccharides production

Solange I. Mussatto [a,*], Luís M. Aguiar [b], Mariana I. Marinha [b], Rita C. Jorge [b], Eugénio C. Ferreira [b]

[a] Department of Biotechnology, Delft University of Technology, Julianalaan 67, 2628 BC Delft, The Netherlands
[b] CEB – Centre of Biological Engineering, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal

HIGHLIGHTS

- Three different fermentation processes for the production of FOS were studied.
- Free or immobilized cells fermentation and solid-state fermentation (SSF).
- The economic aspects and environmental impact of the processes were compared.
- SSF was the most attractive process in both economic and environmental aspects.

ARTICLE INFO

Article history:
Received 18 July 2015
Received in revised form 11 September 2015
Accepted 13 September 2015
Available online 26 September 2015

Keywords:
Fructooligosaccharides
Solid-state fermentation
Coffee silverskin
Economic analysis
Environmental impact

ABSTRACT

Three different fermentation processes for the production of fructooligosaccharides (FOS) were evaluated and compared in terms of economic aspects and environmental impact. The processes included: submerged fermentation of sucrose solution by *Aspergillus japonicus* using free cells or using the cells immobilized in corn cobs, and solid-state fermentation (SSF) using coffee silverskin as support material and nutrient source. The scale-up was designed using data obtained at laboratory scale and considering an annual productivity goal of 200 t. SSF was the most attractive process in both economic and environmental aspects since it is able to generate FOS with higher annual productivity (232.6 t) and purity (98.6%) than the other processes; reaches the highest annual profit (6.55 M€); presents the lowest payback time (2.27 years); and is more favourable environmentally causing a lower carbon footprint (0.728 kg/kg, expressed in mass of CO_2 equivalent per mass of FOS) and the lowest wastewater generation.

1. Introduction

Fructooligosaccharides (FOS) are fructose oligomers with interesting properties such as low caloric value, non-carcinogenicity and effects in decreasing the levels of phospholipids, triglycerides and cholesterol. They also help gut absorption of calcium and magnesium and stimulate the bifidobacteria growth in the human colon (Mussatto et al., 2009; Mussatto and Teixeira, 2010). Due to these important properties, FOS has attracted an increased interest mainly as ingredients for food applications, and their demand has risen rapidly (about 15% per year) in the last years. As a consequence of this, establishing a sustainable and economically viable industrial process for the production of FOS with high yields and productivities has been strongly desired.

Even though most investigations on FOS production are based on submerged fermentation systems, recent studies have suggested solid-state fermentation (SSF) as an interesting alternative to produce these oligosaccharides with higher productivities and yields than those currently obtained on industrial scale (Mussatto and Teixeira, 2010; Mussatto et al., 2013a; Mitchell et al., 2006). A recent study reported by Mussatto and coworkers, in which coffee silverskin was used as solid support and nutrient source in SSF for FOS production, is a good example of that (Mussatto et al., 2013a). This study reports much higher FOS productivity (8.05 g/L h) by SSF than by submerged fermentation with free (5.36 g/L h) or immobilized cells (6.61 g/L h) (Mussatto et al., 2009). SSF is also attractive because low capital costs and low demand of water are required, generating less wastewater as a consequence (Martins et al., 2011). Despite all the positive aspects and encouraging results already obtained, SSF is a process not yet implemented on industrial scale and attention must be paid to the design of the fermenters and to physicochemical parameters of the process (Mitchell et al., 2006).

* Corresponding author. Tel.: +31 (0) 15 278 8789; fax: +31 (0) 15 278 2355.
E-mail addresses: S.I.Mussatto@tudelft.nl, solangemussatto@hotmail.com (S.I. Mussatto).

http://dx.doi.org/10.1016/j.biortech.2015.09.060
0960-8524/

To be implemented on an industrial scale, a process must be profitable and sustainable. In this sense, the experimental point of view may serve as a basis for simulation procedures in order to verify the economic and environmental assessments (Mussatto et al., 2013b). The aim of this work was to perform an economic and environmental analysis of three different processes for FOS production: FCF (submerged fermentation using free cells), ICF (submerged fermentation using immobilized cells) and SSF. These processes were simulated using the software *SuperPro Designer v8.5* and an annual productivity goal of 200 t was considered. Data obtained in previous studies at laboratory scale (Mussatto et al., 2009, 2013a) were used for the simulation, including productivities, product concentrations, yields, and other important thermophysical data. Mass and energy integration concepts were addressed in the development of these processes.

2. Methods

Process design, cost estimation and the project's economic evaluation was developed using the *SuperPro Designer® v8.5* software package (Intelligen Inc., Scotch Plains, NJ). The Waste Reduction Algorithm Graphical User Interface v1.0, or WAR GUI, a program developed by the U.S. Environmental Protection Agency (EPA), was used for the environmental impact assessment.

The stoichiometry of the reactions was determined with the *Solver* add-on from the *MS Excel 2013* tool from *Microsoft Office 2013* where the reactants and reaction products were established based on laboratory scale results (Mussatto et al., 2009, 2013a). The stoichiometric coefficients were determined, for each case, establishing the mass balance with this tool. Solver adjusted the coefficient values – the decision variable – so that the mass balance between products and reactants equalled zero (the constraint cell). Atomic restrictions were not imposed since some molecular formulas are unknown, such as for coffee silverskin or yeast extract. The concentrations and yield values presented in the mentioned studies were used as initial data to calculate the specific yields (GF2, GF3 and GF4), glucose and fructose yields and to calculate the substrate consumption in each case. The known and calculated coefficients were fixed, namely sucrose, glucose, fructose, and FOS (GF2, GF3 and GF4) – in FCF and ICF processes – and sucrose, and FOS in the SSF process. The remaining coefficients were then fitted, resulting in the following stoichiometric reaction equations for the FCF (1), ICF (2) and SSF (3) processes, where "S" stands for sucrose, "YE" yeast extract, "Nu" nutrients, "B" biomass, "G" glucose, "F" fructose and "Su" support (coffee silverskin, because it is also a nutritional source in the SSF process) (Mussatto et al., 2013a).

$$S + 0.93O_2 + 0.09YE + 0.79Nu \rightarrow 1.05B + 1.09CO_2 + 0.45GF2 + 0.16GF3 + 0.03GF4 + 0.20G + 0.03F + 1.04H_2O \quad (1)$$

$$S + 1.50O_2 + 0.07YE + 0.78Nu \rightarrow 0.51B + 0.53CO_2 + 0.52GF2 + 0.18GF3 + 0.03GF4 + 0.23G + 0.03F + 0.51H_2O \quad (2)$$

$$S + 1.33O_2 + 1.90Su \rightarrow 0.78B + 0.64CO_2 + 0.58GF2 + 0.29GF3 + 0.16G + 0.03F + 0.50H_2O \quad (3)$$

Table 1 shows the nutrients, sucrose, yeast extract and immobilization carrier (corn cobs in the ICF case and coffee silverskin in the SSF case) masses that were fed to each system following stoichiometric calculations. The carbon balance of each culture is shown in Table 2. The carbon mass, m_c, was determined using the Eq. (4), where m_{comp} (kg) is the component mass (e.g. sucrose, glucose, GF2...), M_{comp} is its molar mass (g/mol), M_C is the carbon molar mass and N_C is the number of C atoms present in 1 mol of the component.

Table 1
Mass values of sucrose (S), nutrients (Nu), yeast extract (YE) and immobilization carrier (I) – corn cobs in the ICF case and coffee silverskin in the SSF case – to be fed to each system after stoichiometric calculations. Values of annual productivity (P_a) and purity (X_{FOS}) expressed as weight percentage of FOS, for each fermentation process.

	Mass values (kg)				Productivity and Purity	
	S	Nu	YE	I	P_a (t)	X_{FOS} (%)
FCF	1116.0	258.3	129.3	–	148.9	96.6
ICF	972.0	222.3	87.8	48.6	158.3	98.4
SSF	993.6	–	–	79.6	232.6	98.6

FCF: submerged fermentation of sucrose solution by *Aspergillus japonicus* using free cells; ICF: submerged fermentation of sucrose solution by *A. japonicus* using immobilized cells; SSF: solid-state fermentation.

$$m_C = \frac{m_{comp}}{M_{comp}} M_C N_C \quad (4)$$

The difference between the total carbon mass as a reactant and its total mass as a product is explained by the fact that the reactants YE, Nu and Su possess carbon content in unknown proportions. In this way, the resulting difference (kg) represents the total carbon mass present in these reactants fed to the system. For the FCF case: $m_{C(YE)} + m_{C(Nu)} = 160.24$ kg; for the ICF process: $m_{C(YE)} + m_{C(Nu)} = 175.38$ kg; and for the SSF: $m_{C(Su)} = 269.44$ kg; where $m_{C(i)}$ is the mass of carbon present in the component *i*.

2.1. Process model description

The three fermentation processes (FCF, ICF and SSF) have a similar sequence of operations including the FOS synthesis, some purification steps, concentration and sterilization (high temperature sterilization is not recommended to avoid colouring the reaction products (Monsan and Ouarné, 2009). The processes were organized by sections (group of unit procedures) and they all operated with batch fermentations, in order to simulate the conditions of the studies in which this work was based on, during 24 h a day and 330 days per year. The process flowcharts are represented in Figs. 1–3 for the FCF, ICF and SSF processes, respectively.

2.1.1. Free cells fermentation (FCF)

In the FCF process the medium preparation is made in a 6.2 m^3 agitated tank that is fed by two streams: the 'Nutrients' stream – composed by sucrose, yeast extract and micronutrients, according to stoichiometric calculations (see Table 1) – and the 'Water' stream in which its amount depends on the desired concentration for the solution. The outlet stream, 'Medium' is sterilized with 121 °C and sent to an agitated fermenter of 5.4 m^3 that also receives an aeration stream, expressed in gas volume per unit of liquid volume (*V*/*V*) per minute, of 0.5 min^{-1}. The fermentation reaction occurs during 24 h, at 28 °C (Mussatto et al., 2009). Two outlet streams exit the fermenter, the 'Emissions' stream, regarding the gas emissions, and the 'Fermented broth' stream. A sequence of washing steps is performed to ready the fermenter for the next cycle – acid washing with H_3PO_4 20% (*w*/*w*), water washing and alkali washing with NaOH 0.5 mol/L.

The fermented broth is then centrifuged during 6 h, where the biomass is separated from the broth – 2.7% (*w*/*w*) of FOS are lost in this process. The 'Concentrate' stream is sent to the organic waste storage tank and the 'Supernatant' stream is taken to the ultrafiltration stage to separate residual biomass and yeast extract that was not consumed – an efficiency of 97.3% (*w*/*w*) of FOS recovery is