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Techno-economic analysis of a membrane-integrated bioreactor system for production of lactic acid from sugarcane juice

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ABSTRACT

Economic evaluation of a membrane-integrated bioreactor system for lactic acid production from sugarcane juice was performed. The production process consisted of sterilization, fermentation, microfiltration, nanofiltration and final concentration by vacuum evaporation. Membrane recycle fermentor operating at a cell concentration of 22 g/L resulted in a productivity of 53 g/L h with a lactic acid concentration of 106 g/L and a yield of 0.96. The membrane units (cross-flow microfiltration and nanofiltration) and pump contribute about 2% to the total fixed capital cost whereas fermentation unit along with holding tank contribute about 36% to the total fixed capital cost. The two largest cost components were raw material and yeast extract costs contributing about 6% and 87% respectively to the total operating cost. Total product cost stood at 3.15 US $/kg of 80% (w/w) concentrated and 95% pure lactic acid. The study reveals that operating cost could be reduced further by using a cheaper nitrogen source like silk worm larvae or yeast autolysate and installing the lactic acid plant in the sugarcane-growing areas or by optimizing the recycle of nanofiltration retentate to the fermentor.

1. Introduction

In fermentative lactic acid production, cheese whey and molasses have long been used widely as cheap carbon sources but these ingredients cause serious fouling problem in downstream processing making the processes laborious and expensive [1,2]. Sugarcane juice can be a renewable and cheap substitute for these raw materials without possibly inviting so much fouling problem and downstream processing. Sugarcane (*Saccharum officinarum* L.) grows at a faster rate and in enormous quantity than other commercial crops and can be cultivated with sustainable techniques. For years, sugar has been the principal, and virtually only commercial product obtained from cane. Only in the very recent years, sugarcane has been made a part of Brazilian alcohol fuel programme and attempts are being made to produce value-added products other than sugar only from cane juice. The concept of diversification mentioned above and its economic and strategic importance for cane-producing countries has been the focus of attention at several international fora in the past few years. In India, sugarcane is available throughout the year. India ranks second in the world, after Brazil, in terms of sugarcane production. Sugarcane juice is drawing attention increasingly as carbon source due to its possibility of direct conversion into lactic acid without the need for much pretreatment, liquefaction and saccharification [3,4]. Lactic acid is a natural organic acid and has widely been used in food industry as acidulant and preservative. For its biodegradability, bioenvironmental compatibility and availability from renewable resources, polylactide is finding widespread application in a variety of fields [5]. Worldwide demand of lactic acid was estimated to be 130,000–150,000 (metric) tonnes per year [6]. Fermentation-based processes are gaining importance over chemical synthesis one due to its capability of producing pure L-lactic acid as opposed to a racemic mixture of L and D lactic acids in chemical synthesis. But fermentation broth consisting of cells, proteins, unconverted sugars and lactic acid needs to be purified. Integration of a continuous cell-recycle microfiltration system with a fermentor can continuously remove the acid; eliminate product inhibition while permitting high cell concentration in the fermentor through recycle of the microbial cells. Nanofiltration as a purification step was proposed after microfiltration as the nanofiltration membrane show low rejections of lactic acid and high rejection of monosaccharide and disaccharides. However, to make it economically more competitive, production cost needs to be brought down further where the major cost of lactic acid production is involved in its downstream purification that involves quite a number of steps like filtration, acidification, neutralization, crystallization, carbon adsorption, evaporation, ion exchange etc. Such a traditional scheme uses harsh chemicals and they are energy-intensive also [6,7]. Though many membrane-integrated

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systems have been studied for the production of lactic acid, economic studies of the fermentative production have been reported in few studies. In the reported production processes, price for lactic acid ranges from 0.83 to 1.90 US $/kg depending on grade or quality of the acid. Akerberg and Zacchi [4] evaluated the process considering each step batch wise. Some studies [7] evaluated the membrane-integrated system based on batch processing and use of tubular ceramic membrane module and spiral wound module for purification where flux achieved was low. Tejayadi and Cheryan [8] used continuous membrane bioreactor but their process was also energy-intensive because of purification and concentration steps. Their hollow-fiber module was prone to fouling. In one recent study [9], authors reviewed those economics and suggested a membrane-integrated continuous system for production of lactic acid that represents high process intensification. To our knowledge, no techno-economic study for such a promising system has been carried out where the raw material is sugarcane juice which is clean, cheap, easily available and renewable. The present study intends to fill this gap by focusing on two aspects: technical factors concerning the membrane integrated bioreactor system and the production cost of 95% purity lactic acid from sugarcane juice.

2. Materials and methods

2.1. Raw material

Sugarcane is cultivated in about 4.09 million hectares of land producing about 283 million tonnes of cane with an average productivity 72.6 MT/hectare. Mature cane is collected manually or mechanically. Hand cutting is the most usual method. Cane is directly transported to the industry, sampled, washed, weighed, and prepared using rotating knives to shred the stalks into pieces. Shredded cane is subsequently ground in heavy-duty roller mills, which extract the raw juice. The sucrose extraction yield reaches 90–95% in the mills. The fiber fraction of the cane, called bagasse, is generated in this step. This bagasse can be further used for energy production. Furnaces in which the bagasse has traditionally been burned for steam production have energy efficiency rates of approximately 60–65%; whereas it is possible to achieve efficiency rates of nearly 90%, with heat-recovery designs and systems to reduce the final temperature of combustion gases. Cane juice is sent to a clarification process. Clarification of sugarcane juice by microfiltration has been explored extensively both in laboratory and factory trials as permeate is clear, less colored and low viscous. So the cane juice was cold-sterilized/clarified by microfiltration membrane (0.45 μm pore size) and directed to the fermentation stage. The composition of the sugarcane juice used as raw material has been summarized in Table 1.

Table 1
Composition of Indian sugarcane juice used as feed.

Components	Percentage (by weight)
Sucrose	12.5
Fructose	0.66
Glucose	0.84
Fat	0.45
Protein	0.50
Water	72.0
Nonfermentable sugar	0.45
Other reduced compounds	0.35
Organic acids	0.15
Ash	0.60
Others	11.5

Table 2
Summary of the operating conditions selected and the experimental results obtained in each step.

Fermentation
Feed: Filter sterilized sugarcane juice
Feed volume: 20 L
Supplement: peptone 5 g/L, yeast extract 10 g/L
Initial pH = 5.0–6.0
Uncontrolled pH
Microorganism: *Lactobacillus plantarum* NCIM 2912 (National Chemical Laboratory, Pune, Maharashtra, India).
Initial sugar concentration: 126 g/L sucrose, 8 g/L glucose and 6 g/L fructose
Final sugar concentration (after 24 h): 108 g/L sucrose, 2 g/L glucose and 1 g/L fructose
Sucrose conversion: 14%
Lactic acid concentration: 56 g/L
Cell-recycle by microfiltration
Membrane: PVDF-MFB (Sepro Co., USA), cross-flow flat sheet module
Effective membrane surface area: 0.01 m^2 (5 module)
Membrane pore size: 0.45 μm
Operating temperature: 37 °C; operating pressure: 2.5 bar
Cross flow velocity: 2.5 m/s; pH = 4.0–5.0
Permeate flux (steady state): 200 L/m^2 h
Rejection
Microorganism: 100%
Ashes: 2%
Lactic acid: <1%
Purification by nanofiltration
Membrane: NF3 (Sepro Co., USA), cross-flow flat sheet module
Effective membrane surface area: 0.01 m^2 (3 module)
Membrane MWCO: 60% NaCl rejection
Operating temperature: 37 °C; operating pressure: 10 bar
Cross flow velocity: 3 m/s; pH = 4.0–5.0
Permeate flux (steady state): 45 L/m^2 h
Initial sugar concentration: 30 g/L sucrose, 0 g/L glucose and 0 g/L fructose
Final sugar concentration: 0.6 g/L sucrose, 0 g/L glucose and 0 g/L fructose
Initial lactic acid concentration: 118 g/L
Final lactic acid concentration: 106 g/L

3. Experimental

The overall process has been shown in Fig. 1. All the steps (sterilization, fermentation, microfiltration and nanofiltration) involved in the overall process were performed in a pilot scale plant using sugarcane juice as feed. The plant was designed to treat 160×10^6 L/year as feed to get annual production of 16,900 metric tonnes/year. The main experimental results obtained in each step have been detailed in Table 2, along with a summary of the operating conditions selected to perform the experiments. The product obtained was of sufficiently high purity level and could be used as such without further purification and drying. However, for price comparison with commercially available products in the market, additional cost for evaporation was considered in economic analysis following standard design procedure and literature and using data from manufacturing companies.

3.1. Fermentation step

Initially batch fermentation was considered for 24 h and then it was made continuous for 120 h at a 0.5 h^{-1} dilution rate. The 30 L capacity fermentor, keeping working volume at 20 L, was equipped with agitator for continuous stirring and circulating, thermostatic water system with thermocouple for measuring and controlling temperature. pH and dissolved oxygen concentration (DO) were monitored using pH meter (ORION, 4 STAR, THERMO) and DO meter (TOSHBRO, India). Fermentation was done under uncontrolled pH as after 24 h the process was continuous. Nitrogen sparging was done to maintain the anaerobic condition. Initial pH was in the