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Comparative economic assessment of ABE fermentation based on cellulosic and non-cellulosic feedstocks

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ABSTRACT

Biobutanol can become the replacement of petroleum gasoline in near future. However, economic feasibility of biobutanol production from ABE fermentation is suffering due to the unavailability of cheap feedstocks, production inhibition and inefficient product recovery processes. Here, economic analysis of ABE fermentation has been performed based on cellulosic (bagasse, barley straw, wheat straw, corn stover, and switchgrass) and non-cellulosic (glucose, sugarcane, corn, and sago) feedstocks, which are widely and cheaply available in agriculture based countries. Analysis shows that utilization of glucose required 37% lesser total fixed capital cost than the other cellulosic and non-cellulosic feedstocks for the per year production of 10,000 tonnes of butanol. However, the production cost of butanol from glucose was fourfold higher than sugarcane and cellulosic materials because of its (glucose) high cost. The cost of sago also affected threefold production cost of butanol comparative to other feedstocks. Therefore, these two substrates turned the biobutanol production far from being economically feasible. Interestingly, sugarcane and cellulosic materials showed suitability for economically feasible production of butanol with the production cost range of \$0.59–\$0.75 per kg butanol. Consequently, quantitative variation in the design and process parameters namely fermentor size, plant capacity, production yield using sugarcane and cellulosic materials as raw materials, trigger significant reduction in unitary cost of butanol up to 53%, 19%, and 31% respectively. Therefore, these parameters will play significant role in making the butanol production economical from cheaper feedstocks (sugarcane and cellulosic materials). Further, high sensitivity of production cost from the product yield postulates significant manipulation in genome of butanol producing bacteria for improving the yield of ABE fermentation.

1. Introduction

Inflation of crude petroleum prices (e.g., from \$20 per barrel in 2002 to \$140 per barrel in 2008 [1]) is one of the key reasons for accelerated search worldwide for energy alternatives. As a result, interest in bioconversion of alcoholic fuels (e.g., bioethanol, biobutanol, and biodiesel) is rapidly emerging as a topic of great interest to academic and industrial organizations [2]. Currently, bioethanol contributes about 20–30% in fuel market in countries like USA and Brazil whereas it is at very early stage for the development in Asia (only 3.5% share of global production of bioethanol) [3–5]. Another biofuel, biodiesel, is also growing at rates similar to bioethanol [6]. However, biobutanol attracts the attention of researchers and investors in present era due its various advantageous properties, like high calorific value, low freezing point, high hydrophobicity, and low heat of vaporization which are closer to gasoline than other biofuels (Table 1) [7–9]. Unfortunately, one time commercialized acetone–butanol–ethanol (ABE) fermentation is facing severe problems due to feedstock cost, product inhibition, low ABE yield (0.28–0.33 g/g), low productivities ($<0.3\ g\ l^{-1}\ h^{-1}$) and low product concentration ($<20\ g\ l^{-1}$) [10–12]. This low yield has lead to various investigations being carried out for improving the efficiency at process level (fermentation and recovery processes) [13–19] and microorganism level [20,21].

In process development, continuous fermentation with immobilized cells has shown great enhancement leading to productivity levels of $15.8\ g\ l^{-1}\ h^{-1}$ compared to $0.35–0.4\ g^{-1}\ l^{-1}\ h^{-1}$ in batch fermentation, an increase of around 40 times [12]. In addition, such high productivity requires low volume reactors and hence, low capital and operational cost. Also, the byproducts (acetone, ethanol, hydrogen, and carbon dioxide) of ABE fermentation can contribute towards reducing production cost of butanol as their market demand are marked [22]. Fortunately, biobutanol producing organisms are able to co-metabolize multiple sugars which can be hydrolyzed from lignocellulosic materials. Different clostridial strains, namely *Clostridium beijerinckii* [8,13,14,18,23–30] and *Clostridium acetobutylicum* [31–36] have been examined for a wide

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Table 1
Comparison between physico-chemical properties of biobutanol, bioethanol, and gasoline as liquid fuel for vehicles. Gasoline and bioethanol are already being used as fuel in pure and blending manner respectively.

Properties	Biobutanol	Bioethanol	Gasoline
Caloric value (MJ/l)	29.2	21.2	32.5
Air–fuel ratio	11.2	9	14.6
Heat of vaporization (MJ/kg)	0.43	0.92	0.36
Research octane number	96	129	91–99
Motor octane number	78	102	81–89
Solubility in water	Immiscible	Miscible	Immiscible

range of non-cellulosic (i.e. sugar, starch [18,27,29,34]), and cellulosic materials [14,15,30,37,38]. The maximum titer of 21 g l^{-1} of butanol has been achieved in batch fermentation using *C. beijerinckii* BA101 [39], which is a mutant of *C. beijerinckii* NCIMB 8052 [20,21].

Before 1950, conventional raw materials for ABE fermentation were molasses and corn [11,40] and these raw materials were being used for ABE fermentation in countries like USA, Japan, India, Australia, and South Africa. Subsequently, increasing cost of traditional raw materials and introduction of cheaper petroleum fuels lead to a decline in butanol fermentation [11]. However, in recent era, biosynthesis of butanol is being motivated by the success of utilizing cost effective lignocellulosic raw materials. The common examples of these raw materials are agriculture wastes (directly from plant) like barley straw, wheat straw, corn stover, corn fibers, bagasse, and switchgrass [41], which are readily available in agriculture based countries. Therefore, the availability and low cost of these raw materials aid to establish industrial level plants. Before developing commercial scale plants for biobutanol production, the proposed techno-economic models should be evaluated for production cost of butanol. The production data for economic evaluation of future biofuel is rarely available and also depends on regional markets. Therefore, these data can be derived from limited assumptions and available detailed techno-economic models for valid comparison of production costs of biobutanol utilizing different feedstocks [1]. The techno-economical evaluations of ABE fermentation using some non-cellulosic materials (corn and molasses) and cellulosic materials (agriculture wastes) have been performed in previous studies [8,22,42–45]. This paper emphasizes on the techno-economic evaluation of ABE fermentation and comparative analysis between costs of butanol production based on various cellulosic and non-cellulosic materials as available feedstocks. Analysis also focuses on sensitivity of biobutanol price with variation of various design and process parameters. Additionally, we analyzed the future status of biobutanol production on the basis of comparison with future trends of petrochemical based butanol prices.

2. Methodologies for process design and economic feasibility analysis

2.1. Process description

Clostridial species show promise for ABE fermentation using cellulosic (e.g., bagasse, barley straw, wheat straw, corn stover, and switchgrass) and non-cellulosic (e.g., glucose, corn, sago, and sugarcane) feedstocks [8,13,14,18,23–30,34]. However, in this study, the non-cellulosic feedstocks have been selected for comparative analysis as these materials are not food competitive in present world scenario. ABE fermentation process differs based on raw material availability, namely sugarcane, starchy and lignocellulosic materials as shown in Fig. 1. Here, we represent the three broad processes based on sugarcane, starchy materials (corn and sago) and lignocellulosic feedstocks, which are compatible in ABE fermentation.

2.1.1. Sugarcane

The composition of sugarcane is 13.30% sucrose, 4.77% cellulose, 4.53% hemicelluloses, 2.62% lignin, 0.62% reducing sugar, 0.20% minerals, 1.79% impurities, 71.57% water, and 0.60% dirt [46]. On the basis of availability in few countries, sugarcane can be used efficiently for biobutanol production. Key steps involved in sugarcane conversion to biobutanol process are as follows: (i) extraction of sucrose from sugarcane, (ii) fermentation, and (iii) recovery of product and byproducts (Fig. 1a). Filtration is the vital step before fermentation for removing solid residues from sugarcane juice. During the conversion of sugarcane to biobutanol, two byproducts (filtration cake and bagasse) can contribute the credits in economics. Filtration cake can be utilized as fertilizers and bagasse, byproduct of milling section, have potential as substrates for biobutanol production in separate process.

Currently, Brazil is the largest producer of sugarcane. Interestingly, from more than 30 years, sugarcane is being used as a feedstock for the production of bioethanol at industrial level in Brazil [46,47]. The sugarcane production has crossed 450 million tonnes per annum in Brazil. Apart from Brazil, sugarcane and its byproducts after processing in sugar industry are available in other countries like Australia, Thailand, India, Vietnam, Cuba, EI Salvador, Guatemala, Honduras, Nicaragua, Costa Rica, Peru, Colombia, Ethiopia, South Africa, and Zimbabwe [48]. However, because of consumption of less energy for pretreatment, sugarcane is more efficient than corn as a raw material for a fermentation process [49]. Along with sucrose, per ton of sugarcane consists 240 kg of bagasse with 50% humidity; nowadays it is used in boiler to generate the electricity and steam [50]. Further, bagasse may be used as a raw material for biofuel production [51] and can add values in the economics of biofuel production.

2.1.2. Corn

United States produces largest amount (approximately 280 million tonnes per annum) of corn in the world, whereas china comes on second place with approximately 131 million tonnes per annum [46]. Basically, the composition of corn is 61% starch, 3.8% corn oil, 8.0% protein, 11.2% fiber and 16.0% moisture. It can be used directly and in various other forms, like degermed corn [27], extruded corn [34], and liquefied corn starch (LCS) [29], as feedstock of ABE fermentation (Table 2). Laboratory scale studies have been conducted for these forms of corn as a feedstock. On removing the corn oil through oil extraction from grains, this form of corn is called degermed corn [27]. Continuous extrusion cooking of corn kernel was developed for improving product yield, reduction in energy required, and it was helpful in utilizing mycotoxin-contaminated waste corn [34]. However, LCS is a viscous product of corn processing industry. This cost-effective substrate contains 35–40% dry solids as reducing sugars and dextrin. The concentration of glucose, reducing sugar, and sodium metabisulfite ($Na_2S_2O_5$) in LCS was found approximately 5.58, 337.5, and 0.71 g l^{-1} respectively [29].

Corn grains can be milled in dry or wet grind plant. Dry milling includes some advantages like higher yield and low capital cost whereas, wet grinding produces more beneficial byproducts like starch, high fructose corn syrup, corn gluten feed, and corn gluten meal. In wet milling, corn grains are soaked in a mixture of SO_2 and water, in a process called 'steeping', followed by fine grinding, screening and centrifugation for defibrication and degermination (Fig. 1b). Enzymes (amylase) are added to starch solution for its conversion in sugar and then saccharified sugar can be fermented to butanol and byproducts.

2.1.3. Lignocellulosic feedstocks

Sudden rise in the petroleum prices enforced the acceleration in biofuel production from grains, sugarcane, and oilseeds, which is quite beneficial for the countries having suitable resources of