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Economics of Biobutanol: A Review

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ABSTRACT

Due to rapid depletion of fossil fuels and fluctuating market prices of crude oil, extensive research is going on worldwide to find out alternative renewable fuels that can either completely replace the fossil fuels or that can be blended in certain proportions with the fossil fuels without having major modifications in the engines. The most popular alternative liquid fuels are biodiesel and ethanol. However, both of these have limitations that they can be blended with petro-diesel and gasoline only up to 20%. They also suffer from other limitations such as separation from petrol at low temperature and low heat content that reduces economy of blended fuel. A new alternative fuel that has emerged in recent past is biobutanol, which overcomes the problems faced with biodiesel and bioethanol. Biobutanol is manufactured through the process of ABE (acetone-butanol-ethanol) fermentation using various substrates. In this review, we have compared various processes and the substrates used by them from viewpoint of unit price of the butanol. This analysis is based on published literature, but still gives a view into the niche areas for improving economy of the ABE fermentation process and the biobutanol fuel.

Keywords: Biobutanol, ABE fermentation, Alternate fuel, Alcoholic fuel, Extractive fermentation, Bioethanol

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INTRODUCTION

Rapid exhaustion of natural oil and gas, in addition to fluctuating international market prices of crude oil, and concern over greenhouse gas emission through fossil fuel has made hunt for alternate and renewable fuels mandatory. Especially, in the Indian context, necessity of liquid alternate fuels is more marked, as oil reserves in India can provide only 33% of the total petroleum demand, and thus, 67% of the crude oil needs to be imported. This causes heavy burden on Indian economy. Extensive research has taken place in recent past to develop processes for liquid biofuels through enzymatic / microbial conversion of lignocellulosic agro residues. Major alternate liquid biofuels have been biodiesel (which are essentially methyl esters of fatty acids) and bioethanol. However, both of these fuels cannot completely replace petroleum diesel without major modifications in existing engines. Maximum permissible blend of these fuels with petro-diesel compatible with current engines is mere 20%. In addition, these fuels suffer from other limitations such as high heat of vaporization and crystallization at low temperatures.

In the recent past, a new alternate liquid biofuel has emerged in the form of biobutanol. This has several distinct merits over biodiesel and bioethanol. 85% Butanol/gasoline blends can be used in unmodified petrol engines. It can be transported in existing gasoline pipelines and has more heat of combustion or power) than ethanol. Conventionally, acetone-butanol-ethanol fermentation (ABE fermentation), i.e. anaerobic conversion of carbohydrates by strains of *Clostridium* [1], has been the process for production of biobutanol with two major substrates: grain and molasses; and among the A-B-E products, the emphasis has been on acetone. However, in the past one and half decades, intense research has been carried out to increase the selectivity towards butanol using genetically modified strains of *Clostridium* species. In addition, effort has also been dedicated to look for alternate fermentation substrates than molasses and grains, which have several other potential outlets with better cost benefits. Second aspect is the optimization of the fermentation process itself. Although direct microbial transformation of the cellulosic biomass is possible, better way of conversion involves separate hydrolysis of cellulose and fermentation of the resulting hydrolysate. Finally, commercialization of the production process encounters barriers like, cost issues, the relatively low-yield and lethargic fermentations, and problems caused by end product inhibition and phage infections. In addition to being a potential biofuels, butanol is also a valuable C_4 compound for chemical synthesis and a good solvent. The current international price of bulk grade butanol is approx. US $ 4 per gallon (or $1.09 per kg) with a worldwide market of 350 million gallons per year [2].

In this paper we have assessed the economics of different processes of ABE fermentation using two substrates, viz. molasses and corn. To begin with, we have given a brief comparison of biobutanol with other alcoholic fuels such as methanol and ethanol, outlining the definite and distinct merits of butanol over other fuels. Next, we have given a review of various microbial cultures and conventional substrates used for ABE fermentation. This is followed by a brief literature review on yield and productivity of the ABE fermentation process employing different microbial cultures and substrates. Finally, we compare economics of 5 different ABE fermentation processes on the basis of unit price of butanol produced.

Comparative Evaluation of Butanol as an Alternate Liquid Fuel

Table 1: Comparison of the Properties of Different Alternate Liquid Fuels [2]

Fuel	Energy Density (MJ L^{-1})	Air to Fuel Ratio	Specific Energy (MJ/kg air)	Heat of Vaporization (MJ/kg)	Research Octane Number	Motor Octane Number
Gasoline	32	14.6	2.9	0.36	91-99	81-89
Butanol	29.2	11.2	3.2	0.43	96	78
Ethanol	19.6	9.0	3.0	0.92	129	102
Methanol	16	6.5	3.1	1.2	136	104

Before we proceed to the process engineering and economic aspects of ABE fermentation, it would be worthwhile to comparatively access the various liquid alternate fuels. Table 1 lists and compares some common properties of various liquid alternate fuels [2]. It could be seen that properties of butanol match more closely with gasoline than any other fuel. Substitution of gasoline by bio-butanol would result in the fuel consumption penalty ~ 10%, however the mileage of butanol is yet to be assessed. Other distinct merit of butanol over ethanol and methanol are:

1. Greater tolerance to water contamination and less corrosion to the pipeline through which it is transported. Low vapor pressure also makes transportations through pipelines easier.
2. The air to fuel ratio for butanol is close to that of gasoline. This is within the limits of the variation permissible in existing engines. Although complete replacement of gasoline by butanol would require an enhancement of the air-fuel ratio, blends of up to 20% butanol can be easily used in existing engines.

The heat of vaporization of butanol is slightly higher than that of gasoline. Therefore, vaporization of butanol is as easy as gasoline. An engine running on butanol-blended gasoline should not give cold start problem. It must be mentioned that ethanol or methanol blended gasoline is known to give problem in cold weather due to higher heat of vaporization than gasoline.

FERMENTATION CULTURES AND SUBSTRATES

Microorganisms for ABE fermentation are especially sacchrolytic butyric acid producing clostridia [1]. The most popular and extensively implemented strain is *Clostridium acetobutylicum*. In addition, several other species have also been recognized such as *C. acetobutylicum* (which produces isopropanol in place of acetone), *C. aurantibutyricum* (which produces both acetone and isoproanol in addition to butanol [3]) and *C. tetanomorphum* (which produces equimolar amount of ethanol and butanol [4]). In typical batch fermentation, the ratio of ABE solvents produced by *C. acetobutylicum* is 3:6:1 with 20 g/L being maximum concentration. More recently, researchers at University of Illinois [5] have developed the mutant strain named *C. beijerinckii* BA101, which has higher selectivity for butanol as well as higher overall yield of ABE solvents. The ratio of ABE produced by *C. beijerinckii* is 3:16:1 with total solvent yield of 33 g/L. The glucose yield is also higher than other strains, in the range 0.4–0.5. The choice of strain for a particular process depends on the nature of substrate and ratio of the end products required.

The conventional substrates for ABE fermentation are starch (with origin such as maize, wheat, rye etc.) or molasses [6,7]. However, these substrates have been utilized for other purposes such as cattle feed. Cost of substrate is a major factor affecting overall economy of the fermentation, and hence, extensive research has been in recent past on the variety of cheaper substrates, which can substitute for the conventional substrates. New substrates for ABE fermentation include wheat straw, corn fiber, liquefied cornstarch, Jerusalem artichokes, cheese whey, apple pomace and algal biomass, in addition to various other substrates derived from lignocellulose such as pentose sugars and hemi cellulose hydrolysates [8-13]. Jerusalem artichokes contain carbohydrates in the form of short oligomeric fructans with inulinic structure. These need to be hydrolyzed by acid or enzyme prior to hydrolysis. Yield is typically 24 g/L of solvent. Cheese whey needs pretreatment (precipitation and removal of caesin) prior to fermentation. It contains low sugar (4-5% lactose) but is still suitable for ABE fermentation, limited by the product toxicity. The solvent production is in the range of 5-15 g/L with overall yield of 0.23-0.41 g/L. Apple pomace contains 10% w/w carbohydrates with 6% fructose and 23% sucrose. Butanol yield with fermentation of apple pomace is in the range 1.9-2.2%. Algal biomass can also form a suitable fermentation substrate (supplemented with 4% glycerol) with yield up to 16 g/L. The fermentation of algal biomass done with *C. pasteurianum* yields a mixture of butanol and; 1,3 propanediol. More recently, several other substrates have been attempted such as, liquefied corn starch (yield of 81.3 g/L ABE solvents under fed batch mode), wheat straw (yield 12 g/L ABE solvents with simultaneous saccharification and fermentation), and corn fiber hydrolysate (sulfuric acid treatment, yield of 9 g/L ABE solvents). Another potential substrate for fermentation is lignocellulose biomass with 20-40% of hemicellulose. Hemicellulose contains significant amount of pentose sugar (particularly xylose), which is fermented by *C. acetobutylicum*, albeit with lower yield of about 28%. Another approach adopted by some researchers is the direct utilization of biomass using mixed cultures of microorganisms, which have enzymes capable of hydrolyzing cellulose and hemicelluloses [14]. One example in this category is the fermentation of alkali pretreated wheat straw using *C. acetobutylicum* supplemented with cellulolytic fungi *Trichoderma reesei*. This system is reported to produce solvents up to 17.3 g/L with yield of ~ 18%. Co-culturing is also economically viable as it obviates the need for expensive enzymatic hydrolysis. Moreover, fermentation protocol also affects the extent of solvent production and overall yield. An example of this is the recent study on butanol production from wheat straw hydrolysis with different methods by Qureshi et al. [15]. In this study, Qureshi et al. [15] employed five protocols for batch fermentation; viz. pretreated biomass, separate hydrolysis and fermentation of biomass (with out agitation), simultaneous hydrolysis and fermentation with agitation and gas stripping, and finally the fed batch fermentation. The productivities in these protocols were 0.19, 0.14, 0.27, 0.19, 0.31, and 0.36 g/L-h. These results clearly indicated that

Table 2: Summary of Literature on ABE Fermentation with Various Alternate Substrates

Reference	Microorganism used	Substrate	Total yield and productivity of ABE solvents	Other comments
Qureshi et al. **[13]**	C. beijerinckii BA101	Sulfuric acid treated and enzyme treated corn fiber hydrolyzate	1.7 ± 0.2 g/L with acid hydrolyzate; 9.3 ± 0.5 g/L after purification with XAD – 4 resin; 8.6 ± 0.1 g/L with enzyme treated hydrolyzate	Acid treated hydrolyzate contains inhibitory components. Yield improves with removal of inhibitors with XAD – 4 resin. Enzyme treated hydrolyzate does not contain inhibitory components.
Qureshi et al. **[11]**	C. beijerinckii P260	Wheat straw hydrolyzate supplemented with glucose, xylose, arabinose, galactose, mannose	Productivity of 0.36 g/L-h with simultaneous hydrolysis and fermentation. Improvement of 16% in productivity with supplemental sugars.	Fed batch fermentation employed. Cultures effectively uses all sugars. Difficulty was observed for xylose utilization at end of fermentation.
Qureshi et al. **[15]**	C. beijerinckii P260	Wheat straw hydrolyzate supplemented with glucose, xylose, arabinose, galactose, mannose	Solvent yield: I = 9.36 g/L II = 13.12 g/L, III = 11.93 g/L, IV = 17.92 g/L, V = 21.42 g/L. Productivities : I = 0.19 g/L-h, II = 0.14 g/L-h, III = 0.27 g/L-h, IV = 0.19 g/L-h, V= 0.31 g/L-h	Five different processes were investigated fermentation of pretreated WS (I), separate hydrolysis and fermentation of WS to ABE without removing sediments (II), simultaneous hydrolysis and fermentation of WS without agitation (III), simultaneous hydrolysis and fermentation with additional sugar supplementation (IV), and simultaneous hydrolysis and fermentation with agitation by gas stripping (V).
Ezeji et.al **[12]**	C. beijerinckii BA101	Saccharified liquefied corn starch; LCS	Solvent yield: Gas stripped LCS = 23.9 g /L Gas stripped SLCS = 81.3 g/L ABE Productivity: Gas stripped LCS = 0.31 g/L-h Gas stripped SLCS = 0.59g/L-h	Solvent recovery by gas stripping (to relieve inhibition) from the fed-batch reactor fed with SLCS produced 81.3 g/L of ABE compared to 18.6 g/L (control). It as reported that it is not possible for *C. beijerinckii* BA101 to utilize more than 46 g/L glucose.
Ezeji et al. **[20]**	C. beijerinckii BA101	Hydrolyzates of fiber-rich agricultural biomass [e.g. corn fiber, distillers dry grain solubles (DDGS) etc.]	Control: ABE yield = 17.9 g/L ABE productivity = 0.21 g/L-h Inhibition effect on ABE (P2 medium) Yield = 18.3 g/L Productivity = 0.22 g/L-h	Furfural and HMF are not inhibitory to C. beijerinckii BA101, rather they have stimulatory effect on the growth of microorganism and ABE production. The order of sugar preference by C. beijerinckii BA101 can be summarized as glucose > xylose > arabinose > mannose..

Reference	Microorganism used	Substrate	Total yield and productivity of ABE solvents	Other comments
Ezeji et al. **[21]**	C. beijerinckii BA101	Degermed corn/saccharified degermed corn based P2 medium	ABE yield= 14.28 g/L	long-term continuous cultivation of C. beijerinckii BA101 in a degermed corn based medium is not possible due to corn "retrogradation".
Qureshi et al. **[22]**	C. acetobutylicum P260	Corn fiber arabinoxylan (CFAX) and CFAX sugars (glucose, xylose, galactose, and arabinose)	ABE from CFAX and xylose Yield = 9.60 g/L and 0.4 g/g Productivity = 0.20 g/L-h Integrated fermentation hydrolysis and recovery Yield = 0.44 g/g Productivity = 0.47 g/L-h	Integration of hydrolysis of CFAX, fermn. to ABE, and recovery of ABE in a single system is an economically attractive process
Kobayashi et al. **[23]**	C. saccharo perbutyl acetonicum N1-4 (ATCC 13564)	Excess sludge medium supplemented with glucose.	Butanol productivity = 0.55 g/L-h Butanol yield = 9.3 g/L	The content of suspended solids in medium reduced to <50% via acetone-butanol-ethanol (ABE) fermn., thus the sludge was quant. decreased fermentatively using this strain.
Qureshi et al. **[24]**	C. acetobutylicum P262	Whey permeate medium supplemented with lactose	Yield = 0.44 g/g Productivity = 0.21g/L-h	Lactose at 250 g/L was a strong inhibitor to the cell growth of C. acetobutylicum and fermentation Recovery of ABE from oleyl alc is more economical than recovery from the fermentation broth

Simultaneous hydrolysis of wheat straw to sugars and fermentation is an economically viable option. Fed batch fermentation did not give a marked enhancement in solvent production rate; however, when culture was most active, production rates as high as 0.77 g/L h are observed. In another investigation, Ezeji et al. [16] have demonstrated the influence of gas stripping of solvents on fed-batch fermentation techniques, with glucose as the main substrate, the solvent yield without gas stripping use 17.6 g/L with productivity of 0.29 g/L-h. This was improved to 232.8 g/L solvent with productivity of 1.16 g/L-h this amount to four fold increase in productivity and 13 fold rise in the total solvent yield. As an alternative to gas stripping, pervaporative solvent recovery with different types of membranes has also been attempted as a means of reducing solvent inhibition with increase in productivity and overall yield [17]. Table 2 gives a summary of some recently published papers that describe effect of various alternate substrates on the ABE fermentation yield and selectivity.

In the next section we compare the economics of 5 different processes of ABE fermentation using two most popular substrates, viz. molasses and corn. These processes employ two cultures for fermentation, viz. C. acetobutylicum and C. beijerinckii BA 101.

ECONOMIC EVALUATION OF ABE FERMENTATION PROCESS WITH DIFFERENT SUBSTRATES

Various factors affect the economy of the ABE fermentation process. The major among them are mode of fermentation itself (batch, fed-batch, extractive, homogeneous or immobilized cultures), type of microbial strain or culture used for fermentation, the process for solvent recovery, the substrate used and cost of the byproducts (gaseous, liquid and solid) of the process. Using data in the published literature [18,19], we try to find out the major factor that impacts the unit cost of butanol produced. The processes that we compare are batch, fed-batch and continuous immobilized fermentation systems employing two substrates, viz. molasses and corn, employing two techniques for solvent recovery, viz. liquid-liquid extraction using oleyl alcohol + decane as extractant and using two microbial cultures, viz. C. acetobutylicum and C. beijerinckii. The salient features of these processes are given below:

Fermentation processes with molasses as substrate [18]

In this system, we assess two fermentation protocols, viz. batch (without solvent recovery) and extractive fed-batch (with ABE solvent recovery using oleyl alcohol + decane as extractant). In both protocols, C. acetobutylicum culture is employed. The yield of this culture on glucose basis is 0.343 with productivity of 0.45 g/L-h in batch mode and 1.5 g/L-h in extractive mode of fermentation. Cost of substrate, i.e. molasses, is taken to be $100 per ton. Total substrate (molasses) consumption is 824,000 tons for production of 90,000 tons per annum (or 200 million pounds) of butanol.

In batch fermentation, the main substrate, molasses, containing 55% w/w fermentable sugar and 30% w/w non-fermentable solids, is diluted to 60 g/L sugar and mixed with other nutrients in battery of 8 feed tanks. These tanks are preceded by series of 8 sterilizers. The fermentation period is 30 h and the broth contains 13.7 g/L butanol, 5.4 g/L acetone, 1.5 g/L ethanol, 0.2 g/L butyric acid, 0.3 g/L acetic acid and 3 g/L cells. The solvent are first stripped from broth using 50 psig steam. Vapors from the striper contain approximately 70% w/w water and 30% w/w of ABE solvents. Further on, a series of four distillation columns separates the mixture of acetone, ethanol, water and butanol. The stripped broth, mainly comprising of protein, acid, non-fermentable solid and cells is first concentrated to 50% w/w solids in the multiple effect evaporator, and later on dried in rotary dryer. 62 fermenters with 31 pre-fermenters are operated in staggered mode so as to ensure continuous downstream processing.

In fed-batch extractive fermentation, the broth is contacted with solvent (oleyl alcohol diluted with decane to 50:50% w/w). Fermenters are charged with molasses diluted to 900 g/L sugar inoculated with cells grown in the seed fermenter. The broth circulates between fermenter and extraction column. After extraction the broth is sent back to fermenter while the ABE solvent loaded extractant is sent to solvent regeneration column, where the solvents are distilled from extractant, the extractant is recycled to the fermenter while the solvents are separated by further distillation in a series of four columns. At the end of fermentation, the products remaining in the broth are recovered in the same manner as the batch fermentation process. The stillage or the broth remained after stripping off of solvents (containing acids, protein, non fermentable solids and cells) is concentrated in multiple effect evaporator and dried in rotary dryer.

Fermentation processes with corn as substrate [19]

In this system, we assess three fermentation protocols with either simultaneous or post-fermentation pervaporative solvent recovery , viz. batch, fed-batch and continuous immobilized (support: clay bricks) cultures. In all protocols, C. beijerinckii BA101 culture is employed. The yield of this culture on glucose basis is 0.42 with productivity of 0.39 g/L-h in batch mode, 0.98 g/L-h in fed-batch mode and 15.8 g/L-h in immobilized continuous culture mode. The total yield of C. beijerinckii is 33 g/L with distribution of ABE solvents in the ratio 3:16:1. Other salient features of the process are as follows:

(a) Cost of substrate, i.e. corn is taken to be $79.23 per ton ($2.01 per bushel). This substrate is pretreated in the wet milling section of the plant.
(b) One volume of corn steep liquor (100 g/L of solid) is added to five volumes of fermentation medium.
(c) At the end of fermentation, concentration of starch in the reactor is zero and all recovered water is recycled to the fermentation plant, and fermentation gases are compressed and sold.
(d) In case of batch fermentation, the ABE solvents will be recovered by pervaporation at the end, in case of fed-batch mode the culture will simultaneously hydrolyze and ferment the substrate and solvent will be simultaneously recovered. Simultaneous solvent recovery enhances productivity.
(e) For immobilized cultures, tubular plug flow reactor will be use. Due to low residence time of

the substrate in the reactor, starch hydrolysis may not be carried out efficiently. Hence, separate hydrolysis systems using amylolytic enzymes are needed. The reactor blockage problem seen in packed bed reactor can be avoided using fluidized bed mode.
(f) For pervaporation, silicone membranes will be used. Membrane cost: \$ 500 /m^2; Flux: 5 L/m^2-h; Life: 3 years. The effluent will be concentrated by distillation to separate butanol from acetone and ethanol with hexane as entrainer.
(g) Total substrate consumption is 514,000 tons of corn per annum for 120,000 tons of butanol, 24,000 tons of acetone, 7500 tons of ethanol and approx. 233,000 tons of gases. In addition to these, cell mass and polysaccharides are major byproducts. Total amount of byproducts is 445,000 tons.

Economic Comparison

Tables 3 and 4 depict various costs associated with the fermentation process employing molasses. Tables 5, 6 and 7 depict various cost components of fermentation process with corn as substrate. The major cost components are Fixed capital (given as Direct costs inclusive of ISBL and OSBL costs and Indirect costs inclusive of engineering & supervision, construction expenses, contractor's fees and contingency), working capital (taken as 74% of purchases equipment cost), Total production cost (inclusive of raw materials, utilities and fixed charges such as operating labor & supervision, maintenance, operational supplies, laboratory charges, insurance and local taxes and plant overheads) and Byproduct costs. For calculation of per unit cost of butanol, we need to annualize the fixed capital costs. We do so by use of capital recovery factor given as:

$$CPR = \frac{i\left(1+i\right)^n}{\left[\left(1+i\right)^n - 1\right]}.$$

We take a nominal interest rate (*i*) of 10% for all equipment with a life time (*n*) for 10 years. CPR for these values is calculate as 0.163. Product of CPR and total capital investment gives annualized capital cost The per unit cost of butanol (\$ per kg) is then given as:

$$\frac{\text{CPR}\times\text{Fixed Capital + Working capital + Total Production Cost - Byproduct Cost}}{\text{Total production of Butanol}}$$

Using above formula, we calculate the unit production price of butanol for molasses based processes as \$1.46 and \$1.17 per kg for batch and extractive fed-batch fermentation. On the other hand, the corn based processes have unit production price of \$0.44 for batch mode, \$0.42 for fed-batch mode and \$0.4 per kg for immobilized continuous mode of fermentation. Comparing between various cost factors contributing to unit cost of butanol, as mentioned in the above formula, we find that raw material is the dominant factor, cost of which makes maximum contribution. An obvious implication of this analysis is that research on alterate cheap substrates for fermentation is vital to reduction in production cost of biobutanol Another noteworthy fact that emerges from cost analysis is that mode of fermentation does little change to the unit cost of butanol for corn-based fermentation processes. Insensitivity of economics of butanol towards mode of fermentation adds to the flexibility of design of ABE fermentation process. It should also be noted that these are “ex-factory” costs of butanol. The actual sale cost of butanol in the market will be higher due to cost of transportation, storage and other taxes such as sales tax, excise duties and octoroi. Any type of exemption / concession given by in the taxes and duties by the Government would reduce the actual market prices of butanol.

Table 3. Cost Analysis of Batch Fermentation with Molasses as Substrate [18]

Total Production: 90,000 tons per annum of butanol Microbial strain: C. acetobutylicum Total purchased equipment cost: $ 37,280,000		
Sr. No.	**Cost Component**	**$ million**
1.	Direct costs	111.85
2.	Indirect costs	44.82
	TOTAL FIXED CAPITAL	156.67
3.	Working Capital	12.39
	Total Capital Investment	159.66
	Annualized Fixed Capital	26.02
4.	Raw Material	86
5.	Utilities*	26
6.	Fixed Charges	31.27
	Total Production Cost	143.27
7.	Byproduct Cost	49.8
Unit cost of biobutanol ($ per kg)		1.46

*: After energy integration between distillation columns for recovery of acetone, butane, water and ethanol.

Table 4. Cost Analysis of Liquid-Liquid Extractive Fermentation with Molasses Oleyl Alcohol as Extractant [18]

Total Production: 90,000 tons per annum of butanol Microbial strain: C. acetobutylicum Total purchased equipment cost: $ 29,784,000) Extractant: Oleyl alcohol		
Sr. No.	**Cost Component**	**$ million**
1.	Direct costs	89.09
2.	Indirect costs	34.24
	TOTAL FIXED CAPITAL	123.33
3.	Working Capital	12.39
	Total Capital Investment	135.72
	Annualized Fixed Capital	22.12
4.	Raw Material	84.6
5.	Utilities*	9.6
6.	Fixed Charges	26.17
	Total Production Cost	120.37
7.	Byproduct Cost	47.6
Unit cost of biobutanol		1.17($ per kg)

*: After energy integration between distillation columns for recovery of acetone, butane, water and ethanol.

Table 5. Cost Analysis of Batch ABE Fermentation with Corn as Substrate and Pervaporative Solvent Recovery [19]

Total production: 150,000 tons of ABE Solvents with 80% (120,000 tons) Butanol Microbial strain: C. beijerinckii BA 101 Total purchased equipment cost: $14,000,000		
Sr. No.	**Cost Component**	**$ million**
1.	Direct costs	41.02
2.	Indirect costs	16.80
	TOTAL FIXED CAPITAL	57.82
3.	Working Capital	10.36
	Total Capital Investment	68.18
	Annualized Fixed Capital	11.11
4.	Raw Material	42.28
5.	Utilities	10.27
6.	Fixed Charges	14.14
	Total Production Cost	66.69
7.	Byproduct Cost	34.09
Unit cost of biobutanol		0.436 ($ per kg)

Table 6. Cost Analysis of Fed-Batch ABE Fermentation with Corn as Substrate and Pervaporative Solvent Recovery [19]

Total production: 150,000 tons of ABE Solvents with 80% (120,000 tons) Butanol Microbial strain: C. beijerinckii BA 101 Total purchased equipment cost: $13,000,000		
Sr. No.	**Cost Component**	**$ million**
1.	Direct costs	38.09
2.	Indirect costs	15.60
	TOTAL FIXED CAPITAL	53.69
3.	Working Capital	9.62
	Total Capital Investment	63.31
	Annualized Fixed Capital	10.32
4.	Raw Material	42.28
5.	Utilities*	10.27
6.	Fixed Charges	13.28
	Total Production Cost	65.83
7.	Byproduct Cost	34.09
Unit cost of biobutanol		0.417 ($ per kg)

*: After energy integration of the process.

Table 7. Cost Analysis of Immobilized Culture ABE Fermentation with Corn as Substrate and Pervaporative Solvent Recovery [19]

Total production: 150,000 tons of ABE Solvents with 80% (120,000 tons) Butanol Microbial strain: C. beijerinckii BA 101 Total purchased equipment cost: $11,500,000		
Sr. No.	**Cost Component**	**$ million**
1.	Direct costs	33.70
2.	Indirect costs	13.80
	TOTAL FIXED CAPITAL	47.50
3.	Working Capital	8.51
	Total Capital Investment	56.01
	Annualized Fixed Capital	9.13
4.	Raw Material	44.28
5.	Utilities*	10.27
6.	Fixed Charges	11.64
	Total Production Cost	66.19
7.	Byproduct Cost	34.09
Unit cost of biobutanol		0.403 ($ per kg)

*: After energy integration of the process.

CONCLUSION

With rather simple cost analysis, we have tried to highlight the significance of substrate on the production cost of butanol. The corn based processes have significantly low cost of production as compared to the molasses based costs. In addition, these costs are insensitive to mode of fermentation. As compared to the current market price of butanol ($ 1.09 per kg), these costs are at least 40-50% smaller. The economy of corn based processes is not only attributed to low cost of substrate but also more efficient (in terms of total production and selectivity) microbial culture of C. beijerinckii BA 101. It must, however, be noted that cost of byproducts have also contributed significantly to lowering of the cost of butanol. If we do not take into account these, the costs will rise by at least 30%. This result essentially calls attention to operation of the biobutanol product unit with “biorefinery” approach, where an attempt is made to seek outlet/use of all products and not just the main product. On a whole, this paper has highlighted the importance of cost of substrate on the economy of biobutanol production with different process alternative for ABE fermentation.

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