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Bio-butanol vs. bio-ethanol: A technical and economic assessment for corn and switchgrass fermented by yeast or *Clostridium acetobutylicum*

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ABSTRACT

Fermentation-derived butanol is a possible alternative to ethanol as a fungible biomass-based liquid transportation fuel. We compare the fermentation-based production of n-butanol vs. ethanol from corn or switchgrass through the liquid fuel yield in terms of the lower heating value (LHV). Industrial scale data on fermentation to n-butanol (ABE fermentation) or ethanol (yeast) establishes a baseline at this time, and puts recent advances in fermentation to butanol in perspective. A dynamic simulation demonstrates the technical, economic and policy implications.

The energy yield of n-butanol is about half that of ethanol from corn or switchgrass using current ABE technology. This is a serious disadvantage for n-butanol since feedstock costs are a significant portion of the fuel price. Low yield increases n-butanol's life-cycle greenhouse gas emission for the same amount of LHV compared to ethanol. A given fermenter volume can produce only about one quarter of the LHV as n-butanol per unit time compared to ethanol. This increases capital costs. The sometimes touted advantage of n-butanol being more compatible with existing pipelines is, according to our techno-economic simulations insufficient to alter the conclusion because of the capital costs to connect plants via pipeline.

1. Introduction

The issues and merits of biomass-based liquid transportation fuels such as ethanol are under intense discussion in the public [1,2], and in the engineering and scientific communities [3,4]. Nevertheless, the U.S. capacity for fermentation-based ethanol mostly from corn stood recently at over 45.4 $\text{hm}^3\ \text{y}^{-1}$ [5] (current and under construction) exceeding the projections of the United States Department of Agriculture [6]. The U.S. Energy Independence and Security Act (EISA) of 2007 mandates 136.3 hm^3 biofuels y^{-1} for the U.S. market by 2022 of which corn-based ethanol is capped at 56.8 $\text{hm}^3\ \text{y}^{-1}$.

Fermentation-derived butanol has attracted renewed interest as a fuel and recent reviews are available [7,8] in addition to classical papers [9,10]. Announcements by a consortium of companies to produce fuel n-butanol by

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fermentation on the industrial scale have increased the interest [11]. Efforts by other private companies (for example Gevo Inc., CO, or Cobalt Biofuels, CA) to produce butanol have given us a reason to investigate the fundamentals of this biofuel.

Fermentation of biomass to ethanol using the yeast *Saccharomyces cerevisiae* is an ancient technology. Biomass fermentation producing n-butanol using microorganisms of the genus *Clostridium* (termed Acetone Butanol Ethanol or ABE fermentation) based on the seminal work by Weizmann [12] has been performed on the industrial scale (multi-tonne per day per facility) in the U.S. early in the 20th century, in Russia [13] until the late 1980's, in South Africa until the early 1980's, and is currently performed industrially in China with production goals up to 1 million tonnes of ABE solvents per year [14].

It appears that a comparison of the biofuels ethanol and butanol may be useful to see what motivation or de-motivation exists to ferment biomass to butanol (and some ethanol) instead of only ethanol for use as a transportation fuel. A quantitative techno-economic comparison is executed, starting with a classical chemical engineering elemental (carbon) balance for both processes, and using the lower heating value (LHV) of the liquid fuel products per unit mass of feedstock as the criterion of comparison. An economic analysis is then shown for corn ethanol vs. corn n-butanol, followed by an engineering estimate for industrial ethanol + n-butanol production from a cellulosic feedstock compared to ethanol production using an advanced yeast.

2. Background

2.1. *The lower heating value as the basis of liquid biofuel production comparison*

The lower heating value (LHV) of the ethanol (yeast fermentation) or ethanol + n-butanol (ABE fermentation) will be used to compare the conversion of a given mass of feedstock to the target biofuel. The LHV is taken as the heat of combustion at 25 °C and atmospheric pressure reduced by the enthalpy of evaporation of the water formed during combustion since water leaves an internal combustion engine as vapor. Table 1 shows some pertinent and reference values [15–17].

The LHV is used here as a reasonable yardstick since both bio-butanol and bio-ethanol would likely be used in similar internal combustion engines. Energy content per volume of fuel (higher for n-butanol than ethanol), distance driven per volume of fuel etc. are often used in discussing biofuels. The LHV from a given amount of feedstock is a more neutral way of comparing biofuels for similar engines. As an aside, a comparison of bio-ethanol to bio-diesel would be more complex since Diesel engines deliver more mechanical work per unit LHV since they are thermodynamically more efficient than Otto-type engines.

The choice of LHV vs. the sometimes employed HHV (higher heating value) does not change the overall conclusions of the considerations below since the difference is relatively small.

Table 1 – Density and lower heating value (LHV) of fermentation products and gasoline for reference.

	Density [15] $Mg\,m^{-3}$ at 20 °C	LHV $kJ\,g^{-1}$
n-Butanol	0.81	33.4[a]
Ethanol	0.79	27.0[a]
Acetone	0.79	28.7[a]
Hydrogen		121.5 [16]
Gasoline	0.72–0.78 [17]	43.4 [16]

[a] LHV = (Heat of Combustion) – (enthalpy of evaporation of water formed during combustion, at 100 kPa); data from [15].

2.2. *The carbon mass balance as a tool to compare bio-ethanol with bio-butanol*

Fig. 1 shows an overview of the fermentation-based processing to ethanol or n-butanol + ethanol. The requirement for sterility for ABE fermentation will be discussed below.

Carbon is obviously the element of greatest interest when evaluating liquid biofuel production since the ultimate goal is to convert carbon residing in biomass to a liquid hydrocarbon that can be used in an internal combustion engine. The carbon *in starch* is used as the input mass flow for corn since only starch is fermented. Fig. 2 demonstrates that about two thirds of the carbon in the incoming starch is converted to ethanol in the state-of-the-art yeast-based process. The remaining carbon is found as CO_2 gas leaving the fermenters, in biomass produced, and as a small amount of unfermented starch.

A carbon mass balance is a simple and rapid check on the consistency of reported or claimed experimental results and serves as a first level tool for comparing processes. The energy balance is the next step in a meaningful comparison of biofuel production processes since it will reveal the amount of energy needed to produce a unit of energy as target fuel LHV and thereby also paves the way for a subsequent exergy or "quality of energy" analysis. We execute only the carbon mass balance here since the yield of fuel LHV per mass of feedstock is crucial especially when similar processes all based on fermentation and faced with similar downstream issues (separation of dilute alcoholic product from aqueous fermentation broth) are compared.

2.3. *Yield assumptions*

A central issue for any process comparison is the yield here defined as mass of fuel per mass of biomass processed or similarly the LHV of biofuel per mass of biomass processed.

A recent survey of the U.S. fuel ethanol industry by Argonne National Laboratory for the Renewable Fuels Association [18] reported a yield of 0.33 L denatured ethanol per kg corn which is equivalent to about 0.30 kg pure ethanol per kg corn assuming the yield above is taken as ethanol at 20 °C.

The yield of n-butanol per mass of corn is of paramount importance since feedstock costs are often a crucial fraction of the overall production cost of bio-based liquid fuels. Early reports for industrial ABE fermentation of corn by *Clostridium acetobutylicum* are available [19] at a scale of 100 tonnes of solvent produced per day at two plants. About 3 kg of starch