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Which is a better transportation fuel – butanol or ethanol?

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Abstract
This article examines butanol and ethanol as transportation fuels for gasoline-powered engines. This paper examines two aspects. First, the fuel properties of butanol and ethanol are examined and compared to each other. Consequently, butanol overcomes three deficiencies of ethanol. Butanol has a higher energy content, butanol-gasoline blends do not separate in the presence of water, and butanol can be blended with gasoline in any percentage, all the way up to 100%. Second, a review of the fermentation technology is examined for both butanol and ethanol production. Both butanol and ethanol can be fermented from the same feedstocks, which include the sugar and starch crops and lignocellulosic fermentation from wood and crop residues, and fast-growing energy crops like hybrid poplar, switchgrass, and willow. Furthermore, the capital and facilities used to produce ethanol can be switched to butanol fermentation with minimal costs. Thus, society is able to transition away from ethanol and begin to produce butanol with minimal capital and infrastructure costs. Unfortunately, the main drawback to butanol fermentation is its low chemical yield. Until researchers discover or engineer new microorganisms that handle higher butanol concentrations, butanol may not be adapted as an alternative fuel.

Keywords: Alternative energy, Butanol, Lignocellulosic fermentation, Ethanol.

Abbreviations: ABE – Acetone-butanol-ethanol process; EPA – Environmental Protection Agency; GHG – Greenhouse Gas; HHV – Higher heating value; LLV – Lower heating value; MON – Motor Octane Number; MTBE - methyl tertiary-butyl ether; NOX – Nitrogen oxide and nitrogen dioxide; RON Research Octane Number.

1. Introduction

Government and people around the world are concerned about global warming. Global warming is the theory that the buildup of greenhouse gases (GHG) in the earth's atmosphere, like carbon dioxide traps more of the sun's radiation, causing the earth to become warmer. The largest sources of carbon dioxide emissions in the United States are the burning of fossil fuels. In 2006, the burning of coal to generate electricity contributed to approximately 38.9% of the carbon dioxide emissions, while fossil fuels used in transportation, like gasoline and diesel fuel contributed approximately 31.0% [1]. Thus, the United States could mitigate its carbon dioxide emissions by substituting biofuels for fossil fuels used in the transportation sector.

Biofuels mitigate global warming by recycling carbon dioxide from the atmosphere. Plants absorb carbon dioxide and release oxygen back into the atmosphere. The carbon becomes stored in a plant's cellulose, hemicellulose, starches, sugars, and oils. Then man processes the plants into biofuels used in transportation. Then as people drive their cars and trucks, the biofuel is combusted and converted back to carbon dioxide. The carbon recycling is not 100%, because various processing stages of biofuels release greenhouse gases by using fossil fuels as inputs and/or via fermentation. The biofuels are alcohols such as ethanol, and butanol that could be blended with gasoline, and biodiesel that can be used in diesel engines.

Biofuels have four other advantages. First, the United States has a large trade deficit. Reducing petroleum imports could lower the trade deficit and slow down the flow of U.S. dollars into world markets. Second, the Middle East exports petroleum, and a large biofuel industry could slow money accumulated by Middle Eastern governments, hindering their ability to accumulate military hardware. Thus, a large biofuel industry could increase the U.S. energy independence and improve national energy security. Third, biofuels are renewable. The agricultural producers grow the feedstocks for biofuels, potentially boosting employment in rural communities and farmers' income. Finally, biofuels are oxygenates. Oxygenated fuel tends to burn cleaner, reducing tail pipe emissions from hydrocarbons, carbon monoxide, particulate emissions, and sulfur dioxide. Unfortunately, oxygenated fuels tend to raise NOX emissions, which is another regulated pollutant [2-13].

Researchers have extensively studied ethanol and biodiesel. However, one potential overlooked alternative is butanol. Butanol-gasoline blends can be used as fuel for gasoline engines. Butanol was first produced in United States in large quantities from fermentation during World War I and II[1]. However, the growth of the U.S. petroleum industry led to the demise of butanol fermentation, because the petroleum industry could not only produce butanol more cheaply but also sold cheap fossil fuels to power gasoline engines [10, 13, 14, 15]. This article compares ethanol and butanol and shows that butanol may be a superior alternative to ethanol.

2. Butanol and Ethanol fuel properties

Butanol has superior fuel properties when compared to ethanol. The fuel properties depend on the type of butanol. All fuel properties discussed are for n-Butanol where the molecule is a straight chain of four carbon atoms, and the oxygen and hydrogen atoms are attached to the end of the molecule, just like in ethanol. N-Butanol is produced from fermentation through the Acetone-Butanol-Ethanol (ABE) process. However, butanol has another three isomers as isobutanol, sec-Butanol, and tert-butanol[2]. These isomers are not discussed in this paper, because they are not produced by the ABE process.

The first fuel property is restrictions in blending the biofuel with gasoline. Standard car engines can combust fuel up to 15% of ethanol by volume without any engine modifications. Flexible fuel vehicles (FFV) can utilize gasoline-ethanol blends up to 85% ethanol [16, 17]. Butanol-gasoline blends have no restrictions in blending. Since butanol is a longer chain hydrocarbon, it resembles gasoline more closely. Thus, butanol could be blended with gasoline at any concentration. For example, David Ramey drove across the United States in a '92 Buick Park Avenue Ramey on 100% butanol. He did not modify the engine and routinely tested and passed car exhaust emissions at several testing centers across the country [10, 17].

The second fuel property is oxygenates. The U.S. federal law, the Clean Air Act Amendments (CAAA) of 1990, requires gasoline distributors to add oxygenates to fuel. The reformulated fuel is used in cities with high ground ozone concentrations[3] or high carbon monoxide emissions. The belief is having more oxygen in the fuel allows more complete combustion, reducing carbon monoxide emissions [9, 18, 19, 20, 21]. Referring to Table 1, gasoline has almost zero oxygen, ethanol contains 36% oxygen, and butanol contains 22% oxygen. Further, the Environmental Protection Agency (EPA) and several state governments created a strong demand for ethanol, because they phased out the use of methyl tertiary-butyl ether (MTBE). MTBE is an oxygenate and a fuel additive that potentially contaminates underground water sources [20, 22, 23]. Other viable alternatives to MTBE are ethanol and butanol.

The third fuel property is octane number. Octane rating is a measure of how much pressure and temperature is needed to ignite the fuel/air mixture. High-octane fuels prevent premature ignition.

[1] During War World I, British produced butanol as a means to get acetone for munitions production. Butanol was a waste byproduct. Then during the 1920s, the car manufacturers used butanol as a solvent for car lacquers [13].

[2] Atsumi, Hanai and Liao [24] are using E-coli bacteria to produce the branch-chained butanols.

[3] Ironically, the sun's ultraviolet radiation creates surface ozone by the chemical reaction of gases from hydrocarbons (i.e. volatile organic compounds) and NOX emissions [1]. Usually oxygenated fuels tend to increase NOX emissions.

Premature ignition of the fuel can create a pinging or knocking sound from the engine, causing stress on the engine and potentially damaging it [28, 29]. Referring to Table 1, pure butanol has an octane rating of 87, which is comparable to gasoline fuels. However, ethanol has a higher octane rating. This higher octane rating gives ethanol an advantage. Petroleum distributors could buy a cheaper, low-octane fuel and blend it with ethanol to increase its octane. However, octane rating is not the only important fuel property.

Table 1. Ethanol and Gasoline fuel properties

	Units	Gasoline	Pure Ethanol	Pure Butanol
Oxygen Content	100%	Close to 0	36	22
Octane Number	100%	85 to 94	112.5 to 114	87
Reid Vapor Pressure	Bar	0.480 to 1.034	0.159	0.023
Higher Heating Value	MJ / liter	34.8	23.6	-
Lower Heating Value	MJ / liter	31.2 to 32.4	21.1 to 21.3	27.8

Sources: Brekke [25]; Davis and Diegel [26]; Gallagher et al. [18]; Graboski [27]; Reynolds [20]; Sheehan et al. [11]; Wu et al. [15].

Note:
- The Octane Number is the Antiknock Index, which is the average of the Research Octane Number (RON) and Motor Octane Number (MON) [20, 28].
- There is much confusion about the octane number for butanol, because butanol has four isomers. The octane rating in the table is for n-Butanol.

The fourth fuel property is the Reid vapor pressure. A fuel needs a minimum vapor pressure to start a cold engine. Some components of the fuel have to easily vaporize, which is then compressed and ignited. Once the engine becomes warm, then the other components of the fuel will easily vaporize. Referring to Table 1, butanol has a lower Reid vapor pressure than ethanol [10, 15]. Thus, butanol does not easily vaporize which may make it more difficult to start a cold engine. However, the Environmental Protection Agency regulates a gasoline's maximum vapor pressure. Easy vaporization of fuel leads to higher pollution levels, especially during hot summers. The sun's ultraviolet radiation converts these volatile organic compounds along with NOX gases into ground ozone pollution [1]. Petroleum distributors may be able to purchase a cheaper gasoline and blend it with butanol to bring down the fuel's vapor pressure. On the other hand, ethanol-gasoline blends have a complex vapor pressure relationship. Gasoline-ethanol blends can more easily evaporate in the summer, emitting more volatile organic compound into the atmosphere. Petroleum producers would have to buy a more expensive, low vapor pressure fuel to blend with ethanol [20]. Butanol's low vapor pressure is thus both a benefit and disadvantage.

The fifth fuel property is the energy content of the fuel. Combustion of fuel releases heat energy that a car engine converts into motion. Scientists use two measures of heating value: the higher heating value (HHV) and lower heating value (LHV). The higher heating value contains all heat energy released, including the vaporization of water. The lower heating value excludes the energy wasted on water vaporization. Researchers use the lower heating value, because car engines cannot utilize the energy from vaporized water [5, 30]. Referring to Table 1, butanol contains approximately 86% of the energy of gasoline, while ethanol contains approximately 65%. The lower energy content reduces the acceleration and mileage from a gallon of fuel. Thus, butanol fares much better in energy content and is closer to gasoline in energy content. The differences in energy content would lead to different market prices for the fuels. For example, if the price of pure gasoline is \$10.00 per liter, then butanol's price should approximately be discounted to \$8.60 per liter while ethanol should be approximately \$6.50 per liter. The price is based purely on energy content and does not include the consumers' value for protecting the environment.

The last fuel property is moisture and fuel contamination. First, gasoline-butanol blends do not separate in the presence of water, while gasoline-ethanol blends do [9, 16, 20, 21]. Hence, ethanol has to be store in separate tanks at petroleum distribution centers and mixed with gasoline before a tanker truck transports the fuel to gas stations [16, 20]. Second, ethanol cannot be shipped through pipelines, because it could be contaminated with water. Further, ethanol is corrosive to the pipes joints and dissolves some of the impurities and buildup in the pipe [16]. Butanol does not have ethanol's moisture problem [10], but it is not known whether butanol is corrosive to the pipelines or dissolves the impurity buildup in the pipeline. Finally, ethanol-gasoline blends dissolve carcinogenic substances from gasoline like benzene, ethylbenzene, toluene, and xylenes. Over time, the ethanol can steep from fuel lines at filling stations, contaminating the soil [9]. Soil contamination from butanol-gasoline plumes would be much smaller, because butanol is not miscible with water.

Butanol has one property that may hinder the public's adoption of this fuel. Butanol is toxic to humans and life from excessive or prolonged exposure to butanol vapors [31]. However, gasoline is composed of hundreds of compounds and some of these compounds are just as toxic. What makes butanol a better alternative? Butanol has a higher energy content, butanol-gasoline blends do not separate in the presence of water, and butanol can be blended with gasoline at any percentage without modifying the gasoline engine. Furthermore, butanol has a comparable octane level to gasoline and a lower vapor pressure. Gasoline distributors could buy a cheaper gasoline and blend in butanol to meet the EPA's minimum fuel requirements.

3. Butanol and Ethanol production

Butanol is similar to ethanol because both substances are created from fermentation. Fermentation uses microorganisms to consume the sugars and convert them to alcohols. Consequently, producers can make butanol from the same feedstocks as ethanol. Butanol can be produced from sugar and starch crops, agricultural and wood residues, and energy crops. The energy crops are fast growing perennials, such as hybrid poplar, switchgrass, and willow [10, 13, 14, 15]. See Table 2 for U.S. feedstock sources of ethanol. The butanol fermentation has one more feedstock that cannot be utilize by ethanol fermentation. The cheese industry produces whey as a waste product. Thus, butanol fermentation can convert cheese whey into biofuel, mitigating whey disposal problems [10, 13].

Table 2. Common U.S. feedstock sources of sugar and starch

Type	Crops
Sugar crops	Sugar beets, sugarcane, and sweet sorghum
Starch crops	Barley, corn, grain sorghum, oats, potatoes, rice grain, and wheat
Agricultural residues	Bagasse, barley straw, corn stover, oat straw, rice straw, sorghum straw, and wheat straw
Wood residues	Hard wood and soft wood
Energy crops	Hybrid poplar, switchgrass, and willow

The chemical processes for converting pure glucose into biofuel are shown in equations (1) and (2). The first equation is for ethanol and the second is butanol. Theoretically, one metric tonne of sugar will yield 648.2 liters of ethanol or 508.1 liters of butanol. (Assuming the densities are 0.789 kg per liter for ethanol and 0.8091 kg per liter for butanol). However, ethanol and butanol have a major difference. Yeasts, like *Saccharomyces cerevisiae*, have only one chemical reaction for ethanol, which is equation 1. The yeast's chemical conversion ranges from 92 to 92.5% with the remaining sugar being used to create new microorganisms [32, 33]. However, butanol production produces multiple products through the acetone-butanol-ethanol (ABE) process. Microorganisms, such as *Clostridium acetobutylicum* or *Clostridium beijerinckii*, create acetone, butanol, ethanol, carbon dioxide, acetic acid, butyric acid, and trace amounts of hydrogen gas [10, 13, 14, 15, 34, 35, 36].

$$\begin{array}{lll} C_6H_{12}O_6 \rightarrow & 2C_2H_5OH + & 2CO_2 \\ 180.16\,kg & 92.14\,kg & 88.02\,kg \end{array} \tag{1}$$

$$\begin{array}{llll} C_6H_{12}O_6 \rightarrow & C_4H_9OH + & 2CO_2 + & H_2O \\ 180.16\,kg & 74.12\,kg & 88.02\,kg & 18.02\,kg \end{array} \tag{2}$$

The U.S. ethanol industry primarily uses corn as the major feedstock for ethanol production. Although corn contains trace amounts of sugar, the producers convert corn starch into sugar. Starch is composed of long polymers that resemble sugar and a hydrolysis reaction breaks down the starch into sugar, which is shown in equation (3). One kilogram of starch yields 1.11 kilograms of glucose [33, 37]. Thus, one metric tonne of starch can be theoretically fermented into 719.5 liters of ethanol or 564.0 liters of butanol. The gain in matter is from using water as an input. Thus, another benefit from the butanol reaction is it creates water as a byproduct.

$$\begin{array}{lll} \left(C_6H_{10}O_5\right)_n & + n\cdot H_2O & \rightarrow n\cdot C_6H_{12}O_6 \\ 162.14\cdot n\,kg & 18.02\cdot n\,kg & 180.16\cdot n\,kg \end{array} \tag{3}$$

U.S. producers use two technologies to produce ethanol: the corn wet mill or corn dry grind. Corn wet mills are capital intensive industries, because the corn wet mills separate the components of corn kernels in a variety of pure products like starch, germ, fiber, and protein [38]. Corn wet mills range in capacity from 189.3 to 1,249.1 million liters [39]. The corn dry grain is smaller and they grind the corn, hydrolyze the starches, and then ferment the whole mash. Dry grind facilities range in size between 18.9 and 378.5 million liters [38, 39]. Moreover, the corn wet mill exclusively uses corn while the dry grinds can utilize other sugar and starch crops like sugar beets, sugarcane, wheat, and sorghum.

The corn wet mill also produces corn oil, corn gluten feed, corn gluten meal, and starch. The starch could be used to produce ethanol or create a variety of valuable products, which are shown in Table 3. One pound of starch creates corn syrup, dextrose, or high fructose corn syrup (HFCS). HFCS comes as two types: HFCS-42 and HFCS-55. The number indicates the percentage of fructose and correlates to its sweetness level. HFCS-55 is used in carbonated sodas while HFCS-42 is used in jams and confections. Therefore, the ethanol industries compete with the food industry for the corn starch, potentially raising demand and food prices.

Table 3. Corn starch products

Input	Output
1 kilogram of starch	1.3 kilograms of corn syrup or 1.19 kilograms of dextrose or 1.41 – 1.54 kilograms high fructose corn syrup (HFCS)

Sources: National Corn Growers Association [40]; Rausch and Belyea [38]; Light [41]

Both the corn wet mill and corn dry grind could be retrofitted to produce butanol [10, 15]. Both the ethanol and butanol production from the corn wet mill produces the same byproducts: corn oil, corn gluten feed, and corn gluten meal and is shown for one metric tonne of corn in Table 4. The corn dry grind from both butanol and ethanol produces Dried Distiller's Grains with Solubles (DDGS) as a byproduct. Producers can blend DDGS with animal feeds, because the fermentation removes the starch and sugars, thus concentrating the protein, oil, and minerals. Furthermore, the remains of the microorganisms also adds more protein and vitamin Bs [7, 13, 15, 42]. However, DDGS has to be dried to approximately 8% moisture content, which allows the DDGS to be stored or transported long distances. This drying would increase the energy cost of the butanol/ethanol biorefinery. Although the corn dry grind produces more butanol, the corn wet mill produces corn oil which is a valuable byproduct. The fermentation process for ethanol and butanol produces carbon dioxide as a byproduct of the reaction. Carbon dioxide can be sold to the food and soda industries. The food industry uses dry ice to freeze fruits and vegetables, while the soda industry uses carbon dioxide to carbonate sodas. A large ethanol or butanol industry could saturate the market for carbon dioxide gas. For example, the U.S. carbon dioxide market was approximately 5.1 million tonnes in 1995 [43] and 36 ethanol refineries with capacities of 189.3 million liters could supply the carbon dioxide market [44]. Furthermore, carbon dioxide is a greenhouse gas. Thus, this early release reduces the greenhouse gas efficiency of both ethanol and butanol. For example, ethanol produced from corn has an approximately 30.5% offset. Thus, for corn ethanol, the greenhouse gas recycling is approximately 30.5%. Soybean biodiesel has 70.9% offset and burning crop residues to generate electricity tend to have offsets over 86%. If the United States implemented a carbon dioxide permit system, then the soybean biodiesel and co-firing crop residues fare much better and would gain more from the carbon credits. These industries are much more GHG efficient [44].

Table 4. Comparison of Ethanol and Butanol production

Product	Units	Ethanol wet mill (1 metric tonne of corn)	Ethanol dry grind (1 metric tonne of corn)	Butanol wet mill (ABE process) (1 metric tonne of corn)	Butanol dry grain (ABE process) (1 metric tonne of corn)
Ethanol	Liters	371.7	401.5	5.1 to 179.0	5.5 to 193.3
Butanol	Liters	-	-	177.6 to 242.4	191.8 to 261.8
Carbon dioxide	Kg	355.1	383.6	339.1 to 618.5	366.3 to 668.0
Corn oil	Kg	26.8	-	26.8	-
Corn gluten meal	Kg	46.4	-	46.4	-
Corn gluten feed	Kg	241.1	-	241.1	-
DDGS	Kg	-	289.3	-	330.0
Acetone	Liters	-	-	89.5 to 136.2	96.7 to 147.1

Sources: National Corn Growers Association [40]; Rausch and Belyea [38]; Ramey and Yang [10]; Wu et al. [15]

Note:
- The carbon dioxide emissions are only from the fermentation process and do not include the use of fossil fuels used in processing.
- No official numbers for the ABE fermentation from the corn wet mill. However, the wet mill processing leads to an approximate loss of 7.4% of starch [44].

The ABE process for butanol also produces acetone as a byproduct. Acetone is used as a solvent, paint thinner, or degreaser. Although acetone is highly flammable, it is not blended with gasoline. Unfortunately, large-scale production of ABE could flood the acetone market decreasing price [15]. Therefore, acetone may not help offset the production costs for butanol. The acetone could become a waste byproduct.

Large-scale butanol production also would compete with the U.S. food industry for the starch or grains. The grains are used to feed cattle, hogs, and poultry, or exported to foreign markets. Thus, U.S. consumers could potentially pay higher food prices. As an alternative, researchers are focusing on lignocellulosic fermentation. The feedstocks are crop residues, wood residues, and energy crops like hydrid poplar, switchgrass, and willow. Lignocellulosic fermentation is a complex process that hydrolyzes the cellulose and hemicellulose from the feedstocks into five types of sugars: galactose, glucose, and mannose are sugar molecules with six-carbon atoms while xylose and arabinose are sugar molecules with five-carbon atoms [14, 45]. Thus, the ethanol fermentation process requires multiple processing stages and different microorganisms to convert these different sugars into ethanol. Lignocellulosic fermentation also produces lignin as a byproduct [46]. Lignin is a fiber that can be burned to produce electricity. However, producers would have to install expensive capital upgrades to burn lignin for electricity.

The lignocellulosic fermentation process can also be used to produce butanol. However, lignocellulosic fermentation is not widely used by the ethanol and butanol industries. Theoretically, butanol fermentation can simultaneously ferment all sugars into butanol [13, 14, 45] while ethanol fermentation requires multiple processing stages, which increase the operating and capital costs. Wallace et al. [47] estimated a 94.6 million liter ethanol refinery for corn stover would require a $120.7 million investment in 2002 dollars. The U.S. federal government is encouraging the ethanol industry to use more lignocellulosic sources, as stated in the Energy Independence and Security Act of 2007. Although the feedstocks for lignocellulosic fermentation are cheaper, they still have opportunity costs, which are:

1. These feedstocks tend to be bulky and light weight. Thus, the butanol biorefineries would have to be located close to their feedstocks, in order to bring down hauling and transportation costs.
2. Farmers are limited to how much crop residues can be taken off the field. Crop residues provide soil erosion protection and organic material for the soil.

3. Wood residues are used in a variety of products like mulches, plywood, particle boards, and paper.
4. If land is used to grow energy crops, then agricultural producers divert land away from crop production.
5. All lignocellulosic feedstocks can be fired or co-fired with coal to produce bio-electricity. Bio-electricity is extremely greenhouse gas efficient, because the producers haul, process, and dry the feedstock, and then burn it. Butanol requires more processing and hence also releases carbon dioxide during fermentation, lowering its GHG efficiency.

The United States grows a variety of crops. Theoretically, the crops residues could be collected and processed into butanol fuel. Table 5 contains the feedstock composition and the amount of butanol produced if half the sugars are converted to butanol. Glucan, galactan, and mannan create the six-carbon sugars: glucose, galactose, and mannose respectively, while arabinan and xylan create the five-carbon sugars: arabinose and xylose. Although the sugar from xylose is included in the butanol production, the microorganisms have difficulty in converting this sugar into butanol [13, 45]. Furthermore, one kilogram of glucan, galactan, and mannan create theoretically 1.11 kilograms of sugar, while arabinan and xylan create theoretically 1.136 kilograms of sugar [48].

Table 5. Crop residue composition and chemical yield of Butanol

Crop Residue	Glucan (%)	Galactan (%)	Mannan (%)	Arabinan (%)	Xylan (%)	Butanol Production (liters per metric tonne)
Bagasse	40.6	0.8	0.2	1.7	20	180
Corn Stover	40.9	1.0	0.0	1.8	21.5	185
Rice Straw	34.2	0.0	0.0	0.0	24.5	167
Sorghum straw	34.01	0.52	0.2	1.65	14.1	143
Wheat straw	38.2	0.7	0.3	2.5	21.2	179

Sources: Energy Efficiency and Renewable [49]; Kadam [8]; Kim [50]; Tshiteya and Tshiteya [46].

Table 6 contains the prominent grains grown in the United States for 2007. The table also includes the ratio between crop residues to crop production. For example, each metric tonne of corn produced in the United States creates approximately one metric tonne of corn stover. If all the crop residues could be removed and half the sugars are fermented into butanol, then the butanol industry could create 82.1 billion liters of butanol. The annual U.S. gasoline supply was approximately 538.9 billion liters in 2007 [51]. Thus, butanol could supply approximately 15.2% of the transportation fuels market. If all the starch from corn were converted into butanol using the corn wet mill, then that would add another 80.7 billion liters of butanol. This butanol could displace approximately 30% of the gasoline. After adjusting for butanol’s lower energy content, this butanol could displace 26.0% of gasoline. However, this large shift of resources would raise consumer food prices, especially the sugar and animal products. These higher food prices may allow agricultural producers to earn profits and thus, the producers could expand their production. Land that is fallow or set to pasture could be put back into crop production. Unfortunately, this paper does not attempt to measure the agricultural producers' supply response to higher crop prices.

Table 6. Potential U.S. Butanol production from crop residues

Crop Residue	2007 Crop production (metric tonnes)	Crop residue to crop ratio (tonne/crop tonne)	Crop residual (metric tonnes)	Butanol (million liters)
Bagasse	26,490,000	0.60	15,894,000	2,860
Corn stover	332,790,004	1.00	332,790,004	61,699
Rice straw	8,975,273	1.40	12,565,382	2,100
Sorghum straw	12,854,367	1.30	16,710,677	2,396
Wheat straw	56,365,145	1.30	73,274,689	13,112
Total				82,168

Source: Kim and Dale [52]; National Agricultural Statistics Service [53]; Wallace et al. [47]

4. Conclusion

N-Butanol has better fuel properties than ethanol. It has a higher energy content, gasoline-butanol blends do not separate in the presence of water, and no need to modify gasoline engines. Gasoline engines can utilize any gasoline-butanol blends up to a 100% butanol. Moreover, butanol production does not require expensive upgrades to the capital. The infrastructure for ethanol production could be switched to butanol production with minimal capital costs. Thus, society could easily transition to butanol.

Butanol unfortunately has several disadvantages. First and most important, traditional ABE fermentation has low butanol yields, because n-Butanol is toxic to the microorganisms at low concentration levels [13, 14, 17, 24, 35]. However, genetic engineering may allow scientists to create new microorganism that can handle higher concentrations of butanol and increase butanol yields [13, 34, 35]. Further, researchers like Ramey and Yang believe they can improve the butanol reaction by using a continuous, two-stage process. The process may increase butanol yields with no ethanol and acetone being produced as byproducts. In the first stage, the sugar is converted to butyric acid and in the second, the butyric acid is converted to butanol [10].

The second disadvantage is butanol has a legal impediment from the U.S. federal government. Butanol is not recognized as a biofuel and thus, it may not be able to receive the same subsidies as ethanol. Currently ethanol receives a $0.51 per gallon tax break [54, 55]. This subsidy helps offset the production costs for ethanol production, and stimulates the expansion of the ethanol industry.

The last disadvantage is butanol production competes for the same feedstocks that are used by the food industry. A large butanol industry can fuel a large demand for the feedstocks, which would increase food prices. Agricultural producers benefit from the higher prices, but it puts consumers at a disadvantage. At this point, it is not clear whether the higher food prices would fuel the expansion of the agriculture industry. Further study is needed to determine the supply response from agricultural producers.

Another alternative is to produce butanol from lignocellulosic fermentation from crop and wood residues, and the energy crops. Although the feedstocks for lignocellulosic fermentation would have low market prices, they still entail some costs. First, agricultural producers are limited in the amount of feedstocks that can be removed from the land. Second, they also tend to be light weight and bulky which increases the hauling and processing costs. Finally, if the United States incorporated a carbon permit system, then the bio-electric plants would also compete for the same feedstocks, because they are also much more GHG efficient.

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