10-2008

Convergence of Agriculture and Energy: III. Considerations in Biodiesel Production

Jon Van Gerpen
University of Idaho, Moscow

Allan Gray
Purdue University, West Lafayette, Indiana

Brent H. Shanks
Iowa State University, Ames

Beth Calabotta
Monsanto

Drew Kershen
University of Oklahoma, Norman

See next page for additional authors

CAST Commentary
QTA2008-2 October 2008

CAST

The Science Source for Food, Agricultural, and Environmental Issues

Convergence of Agriculture and Energy: III. Considerations in Biodiesel Production

Authors:

Jon Van Gerpen (Chair)
Department of Biological and Agricultural Engineering
University of Idaho
Moscow, Idaho

Allan Gray
Department of Agricultural Economics
Purdue University
West Lafayette, Indiana

Brent H. Shanks
Department of Chemical and Biological Engineering
Iowa State University
Ames, Iowa

Reviewers:

Beth Calabotta
Monsanto
St. Louis, Missouri

Drew Kershen
University of Oklahoma College of Law
Norman, Oklahoma

Alan Weber
MARC-IV Consulting
Columbia, Missouri

CAST Liaisons:

Richard Joost
Department of Agriculture and Natural Resources
University of Tennessee
Martin, Tennessee

Todd A. Peterson
Pioneer Hi-Bred International, Inc.
A DuPont Company
Johnston, Iowa

Introduction

Concern about rising prices and unstable sources of petroleum fuels is driving the search for U.S. domestically produced, renewable transportation fuels, such as biodiesel.

Concern about rising prices and unstable sources of petroleum fuels is driving the search for U.S. domestically produced, renewable transportation fuels, such as biodiesel. Federal incentives of up to $1.10 per gallon have been supplemented by additional incentives and mandated biodiesel use in many states. The Renewable Fuel Standard in the Energy Independence and Security Act of 2007 requires the domestic use of 1 billion gallons of biomass-based diesel fuel by 2012, most of which likely will be biodiesel.

U.S. biodiesel production is primarily from soybean oil, but recent high prices have forced many producers to use lower-cost feedstocks such as animal fats and used frying oils.

U.S. biodiesel production is primarily from soybean oil, but recent high prices have forced many producers to use lower-cost feedstocks such as animal fats and used frying oils. A large portion of domestic production currently is exported to Europe, where the devalued dollar and combined U.S. and European subsidies contribute to the competitive price of imported biodiesel.

Although vegetable oils can be used directly in diesel engines, experience has shown that excessive deposits in the engine cylinder degrade engine performance and increase emissions over time. Conversion to methyl esters allows vegetable oil to be used in diesel engines with fewer problems. These methyl esters have become known as "biodiesel." This document reviews the technology of biodiesel production and the issues and policy implications associated with the expanded use and production of biodiesel.

This material is based upon work supported by the United States Department of Agriculture under Grant No. 2007-31100-06019 / ISU Project No. 413-40-02 and Grant No. 2008-38902-19327 and by the Agricultural Research Service under Agreement No. 59-0202-7-144. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture, Iowa State University, or the Agricultural Research Service.

Biodiesel Production Process

The process for producing biodiesel is simple and the chemistry involved is not complex. The challenge is to economically produce a fuel that consistently meets quality standards, a process that requires significant chemical knowledge and investment in production technology.

The process for producing biodiesel is simple and the chemistry involved is not complex.

Figure 1 provides a block diagram of a biodiesel plant. As shown, oil is co-fed to the *transesterification*[1] reactor with methanol and the base catalyst, usually sodium methylate. Ethanol also can be used, but methanol is used in the United States and Europe because of its lower cost. The triglycerides in the oil are converted to *methyl esters* and

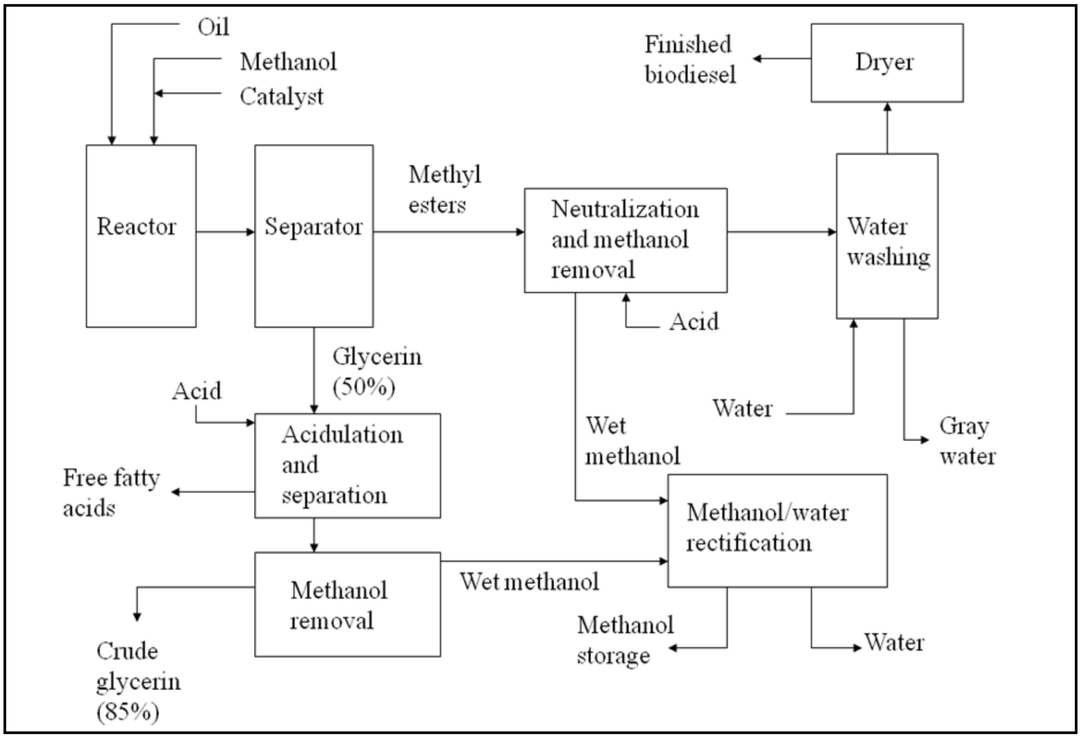

Figure 1. Biodiesel production process (Van Gerpen 2005)

glycerin. After leaving the reactor, the methyl ester and glycerin portions are separated; the alcohol partitions between the two streams while the catalyst primarily partitions to the glycerin stream. The alcohol is removed from the methyl ester stream, which is subsequently water washed to remove impurities and then dried. This dried methyl ester stream is the biodiesel product. In the glycerin stream, the alcohol is removed and the base catalyst is neutralized, allowing some of the salts and the free fatty acids to separate. The crude glycerin stream contains glycerin, water, salts, and most of the impurities present in the original feedstock; it cannot be processed further to biodiesel.

A limited opportunity exists to improve production of biodiesel further, but most changes would not alter the current economies of production significantly. Much research currently is focused on development of a solid catalyst to replace the existing soluble catalyst, which would eliminate the catalyst-recovery step and raise the purity of the glycerin stream.

A limited opportunity exists to improve production of biodiesel further, but most changes would not alter the current economics of production significantly. Much research currently is focused on development of a solid catalyst to replace the existing soluble catalyst, which would eliminate the catalyst-recovery step and raise the purity of the glycerin stream. Much of the value created, however, likely would go to the catalyst provider rather than to the biodiesel producer.

[1] Italicized terms (except genus and species names) are defined in the Glossary.

Renewable diesel, produced by processing vegetable oils or animal fats in conventional petroleum refineries, receives similar tax credits as biodiesel but is not included in the ASTM specification.

The most difficult aspect of biodiesel production is ensuring that the biodiesel product meets quality specifications, a requirement made more difficult when many small facilities produce biodiesel from a variety of feedstocks.

Quality Requirements

As with any fuel intended for use in modern engines, biodiesel must have a high level of quality as defined by standard D6751 of the American Society for Testing and Materials (ASTM 2007). This specification requires that biodiesel be composed of mono-alkyl esters of fatty acids derived from vegetable oils and animal fats. This requirement excludes straight vegetable oil, blends of ethanol and petroleum-based diesel fuel, and fuel produced by thermally processing or *pyrolyzing* vegetable oils or other biomass from the definition of biodiesel. *Renewable diesel*, produced by processing vegetable oils or animal fats in conventional petroleum refineries, receives similar tax credits as biodiesel but is not included in the ASTM specification.

The most common quality concern is fuel containing impurities that can plug filters because it has been reacted incompletely or has aged during storage and formed sediments.

The most common quality concern is fuel containing impurities that can plug filters because it has been reacted incompletely or has aged during storage and formed sediments. A survey by the National Renewable Energy Laboratory in 2006 found that 59% of fuel samples collected at fuel terminals failed to meet the ASTM specification (Alleman, McCormick, and Deutch 2007). Concern about low-quality fuel was heightened by difficulties in implementing the 2% biodiesel mandate in Minnesota in October 2005. This problem motivated the biodiesel industry to place more emphasis on quality; producers were strongly encouraged to become BQ-9000 certified, a voluntary industry-sponsored quality assurance system requiring frequent testing of fuel and in-plant audits to verify compliance. A recent survey of fuel quality based on samples collected directly from producers, weighted to reflect the volume of fuel produced, showed that 89.6% of current biodiesel production met the ASTM specification (Alleman and McCormick 2008).

Attempts to harmonize U.S. and European specifications are promoted by engine manufacturers, but harmonization should be done carefully so that important existing or potential oil feedstocks are not excluded.

In Europe, the specification for biodiesel is EN14214 (European 2003). An important difference from ASTM D6751 is a restriction on the iodine value (a measure of fuel saturation, which affects gelling temperature and shelf life) in EN14214. This restriction has the practical effect of disqualifying soybean-based biodiesel from being used in Europe without blending with biodiesel from other feedstocks, thereby providing an advantage for Europe’s domestically produced rapeseed. Attempts to harmonize U.S. and European specifications are promoted by engine manufacturers, but harmonization should be done carefully so that important existing or potential oil feedstocks are not excluded.

Characteristics of Biodiesel

From a technical perspective, biodiesel provides a number of advantages as a petroleum diesel substitute, without requiring diesel engine modifications. Perhaps most importantly, exhaust emissions from biodiesel are lower than emissions from petroleum diesel.

From a technical perspective, biodiesel provides a number of advantages as a petroleum diesel substitute, without requiring diesel engine modifications. Perhaps most importantly, exhaust emissions from biodiesel are lower than emissions from petroleum diesel. In the most comprehensive comparison of engine dynamometer results, use of B20 (20% biodiesel/80% diesel) decreased hydrocarbons by 21%, carbon monoxide by 11%, and particulate matter by 10%; increasing nitrogen oxides (NOx) by only 2% compared with petroleum diesel use (USEPA 2002). The slight increase in NOx tends to vary with engine type; test cycles typical of urban bus and light-duty vehicle operation actually show a decrease in NOx.

Compared with petroleum diesel, biodiesel also has excellent *lubricity* and *cetane number* properties and is both biodegradable and nontoxic. Other positive aspects of biodiesel are the closed carbon cycle associated with the use of a plant- or animal-derived feedstock and the use of a domestically produced feedstock for biodiesel production.

Several intrinsic technical disadvantages are associated with biodiesel as well. Regardless of feedstock, biodiesel has an energy content of approximately 117,300 British thermal units/gallon, about 8% less than petroleum diesel. Diesel engines operate by injecting a specific volume of fuel, so 100% biodiesel will cause an 8% increase in fuel consumption. Biodiesel gels more readily at low temperatures than petroleum diesel, especially when less-expensive feedstocks such as palm oil and tallow are used. The shelf life of biodiesel is less than petroleum diesel. In the United States, most biodiesel is used in low-level blends (from 2% to 20%), alleviating most of the gelling and shelf life problems. Finally, the most glaring disadvantage of biodiesel is that an insufficient supply of feedstock is available to provide more than 5 to 10% of U.S. diesel fuel needs.

Regardless of feedstock, biodiesel has an energy content of approximately 117,300 British thermal units/gallon, about 8% less than petroleum diesel.

The most glaring disadvantage of biodiesel is that an insufficient supply of feedstock is available to provide more than 5 to 10% of U.S. diesel fuel needs.

Biodiesel Economics

Current Supply and Demand

The biodiesel market is growing rapidly, with approximately 2.61 billion gallons of capacity as of September 2008. There currently are 176 biodiesel producers in the United States, with another 39 plants currently under construction and one undergoing expansion. In 2007, the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri estimated that the industry will have produced 592 million gallons between October 2007 and September 2008 (FAPRI 2008), an increase from only 1 million gallons produced in 1999. The current excess capacity in the industry restricts the price of biodiesel in the marketplace, and the current high price of vegetable oil is placing financial pressure on many biodiesel producers.

The biodiesel market is growing rapidly, with approximately 2.61 billion gallons of capacity as of September 2008.

Role of the U.S. Government

The U.S. government helps establish a market for biodiesel and provides subsidies to the industry. Because underutilized industry capacity already exceeds the 1 billion gallons of biomass-based diesel required by the Renewable Fuel Standard, continued subsidies may be needed. Current government subsidies are substantial, with combined federal and state subsidies sometimes exceeding $1.50 per gallon.

Current government subsidies are substantial, with combined federal and state subsidies sometimes exceeding $1.50 per gallon.

Existing and Potential Feedstocks

Biodiesel can be produced using vegetable oils derived from soybeans, corn, canola, cottonseed, camelina, mustard, and many other plants. Animal fats including beef tallow and pork lard, waste oils, and used grease from restaurants also can be used (USDOE 2008). The total supply of fats and oils within the United States is 36.9 billion pounds (Figure 2). If this entire amount were converted to biodiesel, it would displace only 12% of the 39-billion-gallon U.S. demand for on-highway diesel fuel.

Biodiesel can be produced using vegetable oils derived from soybeans, corn, canola, cottonseed, camelina, mustard, and many other plants. Animal fats including beef tallow and pork lard, waste oils, and used grease from restaurants also can be used.

Of the total supply of fats and oils, soybean oil amounts to 20.7 billion pounds, or almost 56% of the total stock. Inedible tallow from slaughter facilities is second in available supply with 3.8 billion pounds. According to census estimates (U.S. Census Bureau 2008), soybean oil accounted for approximately 79% of the production of methyl esters in the United States during the 2007 calendar year (USDOE 2008). This situation contrasts

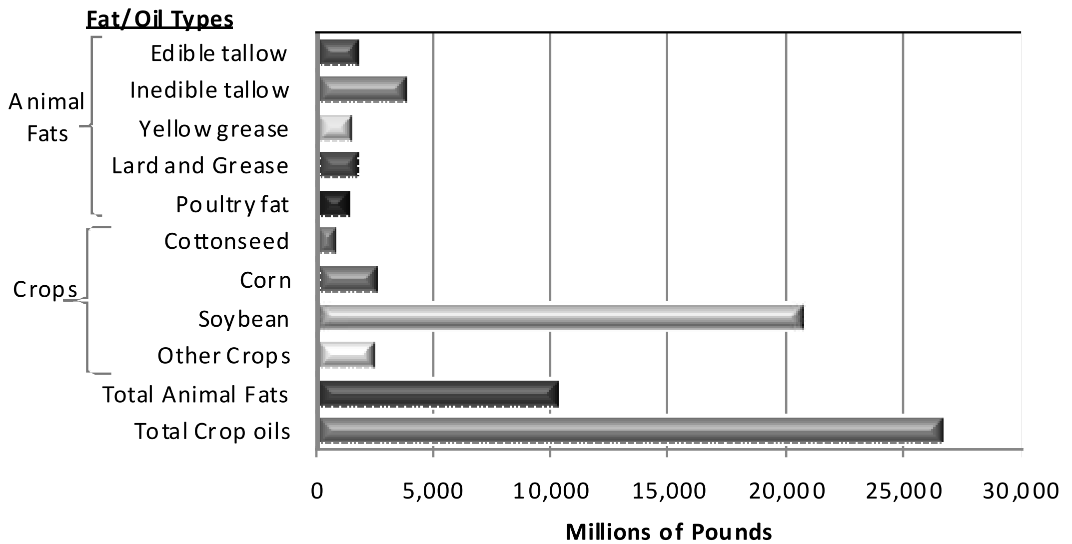

Figure 2. U.S. supplies of potential biodiesel feedstocks (U.S. Census Bureau 2008)

The sudden increase in demand for corn acres to produce ethanol has caused concern about the future availability of acres for soybeans in the United States.

with the European industry, where a variety of rapeseed similar to canola is the most common feedstock for biodiesel.

Slightly more than 1 gallon of crude soybean oil produces 1 gallon of biodiesel. Soybean oil accounts for 80 to 90% of the cost of production for biodiesel. The sudden increase in demand for corn acres to produce ethanol has caused concern about the future availability of acres for soybeans in the United States. Worldwide soybean production growth rates are expected to slow while demand continues to increase. The feedstock costs for biodiesel are substantially higher than costs for crude petroleum, putting biodiesel at a cost disadvantage to petroleum diesel before the production process even begins.

Production Costs

As long as there is a price discrepancy between biodiesel and petroleum diesel, it is difficult to imagine the U.S. biodiesel industry expanding much beyond the renewable fuels standard set forth in the 2007 Energy Bill without substantial increases in the wholesale cost of petroleum diesel, additional subsidies, or substantial technological advances.

Transesterification is a relatively simple process. Biodiesel production costs are dominated by the costs of feedstocks, followed by chemical inputs, energy, and water. Chemical costs range from $0.30 to $0.40 per gallon of biodiesel, and utilities are normally $0.05 to $0.10 per gallon. In today's energy environment, costs to convert the oil normally are estimated at about $0.58 per gallon including labor. The process of producing biodiesel results in the production of glycerin as a coproduct. Unfortunately, the increased production of biodiesel worldwide has glutted the market for crude glycerin, and its value has declined to a range of $0.06 to $0.10 per gallon of biodiesel. There are, however, some recent indications of price recovery as new markets develop.

The economies of size in both investment costs and labor savings have led to the construction of increasingly larger biodiesel plants. Taking into account investment costs, return rates, feedstock costs (at $0.60/lb), federal subsidies, and other incentives, a plant would need to receive $4.08 per gallon for its biodiesel production as a break-even price. If the plant were to use animal fats and greases, the annualized cost of production could drop, because the feedstock costs currently are about 25% lower than the cost of vegetable oils (USDA–AMS 2008). Price comparisons between biodiesel and petroleum diesel also should reflect biodiesel's 8% lower energy content.

As long as there is a price discrepancy between biodiesel and petroleum diesel, it is difficult to imagine the U.S. biodiesel industry expanding much beyond the renewable fuels standard set forth in the 2007 Energy Bill without substantial increases in the wholesale cost of petroleum diesel, additional subsidies, or substantial technological advances. Those plants already in production may be able to continue producing biodiesel because the investment cost is not a part of the production decision, which would allow those plants using animal fats to produce at a price competitive with the domestic wholesale petroleum diesel market. For those existing plants using vegetable oils, one of three scenarios is likely: (1) decreasing production to contain losses, (2) selling product in a state with a mandate or large tax incentive, or (3) blending their biodiesel with petroleum diesel in the United States to receive the blender credit, then shipping the blended biodiesel product to the European market to collect the biodiesel subsidies in the European Union.

Technological Advances that May Improve the Economics of Biodiesel

Unlike ethanol, potential technological improvements in the production of biodiesel from soybean oil are limited. It is chemically impossible to improve the conversion of 1 gallon of soybean oil to 1 gallon of biodiesel. Thus, technological advances in the biodiesel industry are more likely to come from improvements in the oil production from the renewable source (mainly oil crops).

It is chemically impossible to improve the conversion of 1 gallon of soybean oil to 1 gallon of biodiesel. Thus, technological advances in the biodiesel industry are more likely to come from improvements in the oil production from the renewable source (mainly oil crops).

One possible technological improvement is incremental improvement in the oil yield per acre from existing crops. For soybeans, however, an increase in oil production usually means a decrease in soybean meal production. Currently, soybean meal continues to be the main economic engine for the value of soybeans, which may limit the transition to soybeans with higher oil content. The FAPRI forecasts suggest, however, that within the next 2 to 3 years soybean oil may become the dominant economic driver of the soybean processing industry. Paradigm changes such as this transition and concerns about the effects of biofuels on food prices are becoming major agricultural issues.

The biodiesel industry may seek alternative oil crops to source their feedstock. For example, a typical Midwest soybean farm can produce approximately 60 gallons of soybean oil per acre. A typical acre of canola can produce 111 gallons of oil per acre, but cannot compete economically with a corn–soy crop rotation. This difference in production from current varieties of each crop suggests that expansion of oilseed acres to include alternative feedstocks such as palm, canola, camelina, jatropha, and algae, as well as recovery of currently unused feedstocks such as corn oil from dry mill ethanol plants, may become important to sustain growth rates in biodiesel production.

This difference in production from current varieties of each crop suggests that expansion of oilseed acres to include alternative feedstocks such as palm, canola, camelina, jatropha, and algae, as well as recovery of currently unused feedstocks such as corn oil from dry mill ethanol plants, may become important to sustain growth rates in biodiesel production.

Energy Balance

The ratio of the energy contained in a fuel to the fossil energy required to produce it frequently is cited as a measure of the fuel's sustainability. Fuels produced from fossil sources such as gasoline or natural gas always have ratios less than one, because a portion of the energy supplied in the crude petroleum is required to convert this product to a more usable form. A well-regarded study for the energy ratio of soybean-oil-based biodiesel in the United States showed that the fuel contained 3.2 times more energy than was required to produce it (Sheehan et al. 1998). Related to the energy ratio is the net production of greenhouse gases. Current research indicates that the use of biodiesel decreases CO_2 emissions by 78% compared with petroleum-based diesel fuel (Sheehan et al. 1998).

The ratio of the energy contained in a fuel to the fossil energy required to produce it frequently is cited as a measure of the fuel's sustainability.

A well-regarded study for the energy ratio of soybean-oil-based biodiesel in the United States showed that the fuel contained 3.2 times more energy than was required to produce it.

There is concern that the energy ratio calculation treats all forms of energy as if they were equivalent.

Further expansion of the industry will require new or larger sources of vegetable oils and animal fats that can be produced at prices that allow biodiesel to compete with petroleum-based diesel fuel.

There is concern that the energy ratio calculation treats all forms of energy as if they were equivalent. This approach does not recognize that some fuels are more useful than other fuels for certain applications. For example, coal is less expensive than gasoline in large part because coal is not suitable for use as a transportation fuel. A process to convert coal to gasoline would benefit society substantially in spite of having an energy ratio less than one. From this perspective, biofuels such as biodiesel and ethanol can have a very beneficial effect on the world's fuel supply (Dale 2007; Farrell et al. 2006; Sheehan et al. 1998). Most of the energy input to the production of these fuels is natural gas for fertilizer production to grow the crop and process heat for the chemical reactions and distillations. Their production processes could be viewed as conversions of a gaseous fuel that is difficult to use for transportation to a liquid fuel that is easily used in existing vehicles.

Conclusion

The U.S. biodiesel industry is struggling because of high prices for its feedstocks, vegetable oils, and animal fats. High feedstock prices also are affecting international biodiesel production, but requirements to lower greenhouse gas emissions continue to stimulate interest in the fuel.

Biodiesel is developing into a widely accepted alternative fuel. Quality concerns have been addressed, and most fuel today integrates easily into the existing diesel fuel infrastructure. Further expansion of the industry will require new or larger sources of vegetable oils and animal fats that can be produced at prices that allow biodiesel to compete with petroleum-based diesel fuel. Research into the new sources and into technology to develop underutilized feedstocks is needed.

Glossary

Cetane number. A quality parameter for diesel fuel (analogous to the octane number for gasoline) that characterizes the fuel's ignition properties in the engine.

Glycerin. A syrupy liquid with many uses in the production of cosmetics and other personal care products.

Lubricity. A measure of a liquid's ability to serve as a lubricant between two surfaces by reducing friction and wear.

Methyl esters. The chemical constituents of biodiesel. These compounds are formed most frequently by reacting triglycerides with methanol. When ethanol is used, the products are ethyl esters.

Pyrolyzing/pyrolysis. A thermochemical process that involves high temperatures—usually with a lack of oxygen—so the biomass reactants do not combust, but rather break down to form complex mixtures of oxygenated hydrocarbons.

Renewable diesel. A term usually used in reference to fuels produced from vegetable oils and animal fats, but which are not alkyl esters and thus do not qualify as biodiesel.

Transesterification. A chemical reaction forming the alkyl esters that make up biodiesel, consisting of the reaction of an ester (a triglyceride) and an alcohol (methanol) to form another ester (methyl ester-biodiesel) and another alcohol (glycerol).

Literature Cited

Alleman, T. L. and R. L. McCormick. 2008. *Results of the 2007 B100 Quality Survey*. Technical Report NREL/TP-540-42787. National Renewable Energy Laboratory, Golden, Colorado.

Alleman, T. L., R. L. McCormick, and S. Deutch. 2007. *2006 B100 Quality Survey Results: Milestone Report*. Milestone Report NREL/TP-540-41549. National Renewable Energy Laboratory, Golden, Colorado.

American Society for Testing and Materials (ASTM). 2007. Standard specification for biodiesel fuel (B100) blend stock for distillate fuels. In *Annual Book of ASTM Standards*. American Society for Testing and Materials, West Conshohocken, Pennsylvania.

Dale, B. E. 2007. Thinking clearly about biofuels: Ending the irrelevant ''net energy' debate and developing better performance metrics for alternative fuels. *Biofuels, Bioproducts, Biorefining* 1:14–17.

European Committee for Standardization. 2003. Biodiesel Standard EN14214. Brussels, Belgium.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare, and D. M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311:506–508.

Food and Agricultural Policy Research Institute (FAPRI). 2008. *U.S. Baseline Briefing Book: Projections for Agricultural and Biofuel Markets*. FAPRI-MU Report #03-08. University of Missouri, Columbia.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri. 1998. *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*. Final Report NREL/SR-580-24089. National Renewable Energy Laboratory, Golden, Colorado.

U.S. Census Bureau. 2008. Fats and Oils, Production, Consumption, and Stocks–2007. M311K(07)-13, http://www.census.gov/industry/1/m311k0712.pdf (3 October 2008)

U.S. Department of Agriculture–Agricultural Marketing Service (USDA-AMS). 2008. National Weekly Ag Energy Roundup, April 25, 2008, http://marketnews.usda.gov/lsmnpubs/PDF_Weekly/AgEnergy.pdf (3 October 2008)

U.S. Department of Energy (USDOE). 2008. Alternative Fuels and Advanced Vehicles Data Center, http://www.eere.energy.gov/afdc/fuels/biodiesel_production.html (3 October 2008)

U.S. Environmental Protection Agency (USEPA). 2002. *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*. Draft Technical Report EPA420-P-02-001.

Van Gerpen, J. 2005. Biodiesel processing and production. *Fuel Process Technol* 86:1097–1107.

Citation:
Council for Agricultural Science and Technology (CAST). 2008. *Convergence of Agriculture and Energy: III. Considerations in Biodiesel Production.* CAST Commentary QTA2008-2. CAST, Ames, Iowa.