Biodiesel:
An Alternative Fuel for
Compression Ignition Engines

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Abstract. Biodiesel is an alternative fuel for diesel engines that is produced by chemically combining vegetable oils and animal fats with an alcohol to form alkyl esters. Extensive research and demonstration projects have shown it can be used pure or in blends with conventional diesel fuel in unmodified diesel engines. Interest in biodiesel has been expanding recently due to government incentives and high petroleum prices. This paper reviews the history of biodiesel development, production practices, and the technology to utilize the fuel without problems. A technical consensus has developed that quality is the most important criterion of successful biodiesel use and that fuel should meet the ASTM specification for biodiesel, D6751. When the fuel meets this standard, it has been shown to provide improved lubricity, higher cetane number, lower emissions of particulate, carbon monoxide, unburned hydrocarbons but higher level of oxides of nitrogen. While the current availability of vegetable oil limits the extent to which biodiesel can displace petroleum to a few percent, new oil crops could allow biodiesel to make a major contribution in the future.
Keywords: Biodiesel, Diesel, Renewable fuel, Alternative fuel.

Introduction

The esters of vegetable oils and animal fats are known collectively as *biodiesel*, a renewable alternative fuel that has been shown to be direct replacement for diesel fuel in compression ignition engines. Biodiesel has an energy content that is about 12% less than petroleum-based diesel fuel on a mass basis. It has a higher molecular weight, viscosity, density, and flash point than diesel fuel. When biodiesel is compared to conventional diesel fuel in engine tests, the power and fuel consumption are in nearly direct proportion to the fuel's energy contents. Biodiesel is an oxygenated fuel, 10% to 11% oxygen by weight, and produces less unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) than diesel-fueled engines. Carbon dioxide (CO_2) is recycled through the process of photosynthesis in growing the oilseeds making biodiesel nearly CO_2 neutral. Oxides of nitrogen (NO_x) are increased by 10% to 15% when fueling with 100% biodiesel. Biodiesel fuels are good for the environment because they are also readily biodegradable, a benefit in case of spills.

The National Biodiesel Board (NBB) suggests two definitions for biodiesel. For general audiences, "biodiesel is a domestic, renewable fuel for diesel engines derived from natural oils like soybean oil, and which meets the specifications of ASTM D 6751." A second, more technical, definition of biodiesel is "a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of ASTM D 6751" (NBB, 2006).

Long-term engine tests have shown that with use of biodiesel, engine performance, wear, and injector coking equal or surpass that when the engines are fueled with diesel fuel (Perkins et al., 1991).

Two limitations to biodiesel use are the cost to produce the fuel and the potential production capacity. Recent federal and state incentives, which total over $1 per gallon ($0.26/liter), and rapidly rising diesel fuel prices have made biodiesel very competitive with diesel fuel and in some cases less expensive. Production of biodiesel is limited by available land area. It is estimated that 65% of the total U.S. agricultural land would be required to grow the vegetable oil needed to replace the 33 billion gallons (125 billions liters) of diesel fuel used in U.S. on-road transportation (Peterson et al., 1995).

History

It is very common for articles on biodiesel to start by claiming that Rudolph Diesel fueled one of his early engines with peanut oil at the Paris Exhibition in 1900. For an excellent discussion of the history as it involved Rudolph Diesel, the authors suggest Knothe (2005b), who has prepared a comprehensive review of the literature available from the Diesel era. Knothe (2005b) states that Diesel did not actually use peanut oil himself but was describing a test

conducted by another company. In any case, the vegetable oil testing was considered to be a success and offered the potential for remote colonies to be self-sufficient in fuel.

Knothe (2005b), Quick (1980a), and others report that in a 1912 speech, Rudolf Diesel said "...the use of vegetable oils for engine fuels may seem insignificant today, but such oils may become, in the course of time, as important as petroleum and the coal-tar products of the present time." It is difficult to determine to what extent Rudolph Diesel believed that vegetable oils would someday be a major source of fuel for his engines. It would have been impossible for him to foresee the massive use of diesel power as we know it today. In 1912, the thought of using 33 billion gallons (125 billion liters) of on-road diesel annually in the U.S. would have been staggering. It was known in Diesel's time that vegetable oil in the raw form was sufficient to start and power a diesel engine. Since then, we have learned that raw oils cause engine deterioration when the use is continued for an extended period of time and that better success is observed when the oils are first converted to methyl or ethyl esters, which have come to be known as biodiesel. This success was acknowledged with the approval of a specification by the American Society for Testing and Materials in 2002 (ASTM, 2002). With few exceptions, Diesel's engine has been almost exclusively fueled with petroleum-based diesel fuel until very recently. Exceptions to this can occasionally be found, such as some unique situations during World War II and in some areas where diesel was expensive or unavailable.

The real interest in vegetable oil fuels began in the late 1970s during the OPEC oil embargo. A significant conference which documented the studies of the late 1970s was held in August, 1982, under the auspices of the American Society of Agricultural Engineers (ASAE; now the American Society of Agricultural and Biological Engineers, ASABE). The conference was held in Fargo, North Dakota, and was entitled simply "Vegetable Oil Fuels." A 400-page proceedings of this conference containing 44 articles was published by the ASAE (ASAE, 1982). Contributions were made by leading researchers from around the world. While at that time the majority of the papers dealt with the potential of raw oils as fuel, several papers discussed the production of esters and the use of the esters as engine fuels that showed more promise than did the raw oils. Scientists from Brazil, the Republic of South Africa, the Northern Regional Research Center in Peoria, Illinois, the University of North Dakota, and Deere and Company all made presentations regarding the conversion of vegetable oil, primarily sunflower oil, to methyl esters. References to transesterification of vegetable oils cited by these authors include one published in the *Journal of the American Chemical Society* in 1911, and others in 1944, 1948 (process patents), 1949, 1974, etc. The transesterification process was well known and useful for purposes other than diesel fuel well before the time of this 1982 conference. What was occurring in 1982 was an adaptation of the transesterification process to produce a fuel.

Borgelt et al. (1994) report that a 1949 U.S. Department of Agriculture (USDA) publication included an annotated bibliography of 99 references on the use of vegetable oil as fuels between 1920 and 1947 (Shay, 1993). They also report that a 1952 review of research conducted in India, China, Belgium, and other countries concluded that "even with the existence of technical problems, vegetable oil as fuel showed promise" (Aggarwal et al., 1952). Borgelt et al. (1994) also report interest in vegetable oils during World War II. Among these was a 1938 paper by John Walton in *Gas and Oil Power* entitled "The Fuel Possibilities of Vegetable Oils" followed by a 1942 paper by R. H. Seddon in the same journal entitled "Vegetable Oils in Commercial Vehicles" (also cited in Baranescu and Lusco, 1982).

The first known report of using esters of vegetable oils as a motor fuel was described in a Belgian patent granted to G. Chavanne (1937) of the University of Brussels on 31 August 1937. Sims (1981b), in a communication to C. Peterson, reported on their work with esters which indicates that he and Dr. Roger Korus of the University of Idaho were in correspondence regarding work on development of ester fuels. Pishinger et al. (1982a,b) report on using esters in Brazil. The first report on use of esters in the U.S. was evidently by Fort et al. (1982), reported in an SAE paper titled, "Evaluation of Cottonseed Oils as Diesel Fuel." This study was closely followed by two other important studies on using ester fuels, Geyer et al. (1984) and Wagner et al. (1984). These early studies concluded that a significant factor that slowed development of vegetable oil esters was cost. In the 1980s vegetable oils were considerably more expensive than diesel and it was mentioned that the additional processing would only drive the cost higher.

Early papers in the evolution of vegetable oil fuels (all cited in ASAE (1982)) were a 1978 ASME paper by Engelman, Guenther, and Silvis entitled "Vegetable Oil as a Diesel Fuel;" a 1979 report by Erickson and Dixon to the American Soybean Association entitled "Soy Oil as Diesel Fuel; Economic and Technical Perspectives;" and a 1980 ASAE report by Peterson, "Vegetable Oils—Renewable Fuels for Diesel Engines." Other early papers which are included in citations within the papers in ASAE (1982) include Peterson et al. (1981), entitled "Vegetable Oil as an Agricultural Fuel for the Pacific Northwest;" a paper by Bruwer et al. (1980) entitled "The Utilization of Sunflower Seed Oil as a Renewable Fuel for Diesel Engines;" an article by Quick (1980a) for *Power Farming* magazine entitled "An In-Depth Look at Farm Fuel Alternatives;" an ASAE paper by Quick (1980b) entitled "Developments in Use of Vegetable Oil as Fuel for Diesel Engines;" a paper from Canada by Strayer et al. (1980) entitled "Canola Oil as a Fuel for Diesel Engines;" a paper by Cochran et al. (1980) for *Agricultural Energy,* "Diesol—An Alternative Fuel for Compression Ignition Engines;" a research report from North Queensland, Australia, by Galloway and Ward (1980), "Comprehensive Testing of Modern Compression-Ignition Diesels under Extended Operations on Vegetable

Oils" and by Kaufman et al. (1981), "Performance of Diesel Oil and Sunflower Oil mixtures in Diesel Farm Tractors." The references to research on vegetable oil fuels had expanded in 1981 to be too voluminous to list.

The overall theme and outcome of the 1982 ASAE conference was that raw vegetable oils, while showing promise, had a tendency to cause injector coking, polymerization in the piston ring belt area causing stuck or broken piston rings, and a tendency to thicken lubricating oil causing sudden and catastrophic failure of the rod and/or crankshaft bearings. A method for reducing the viscosity of the oil and its tendency to polymerize were viewed as of the highest priority to make use of vegetable oils successful and the most likely candidate for that was transesterification of the vegetable oil.

Research into the use of transesterified sunflower oil and refining it to the diesel fuel standard was initiated in South Africa in 1979 (Bruwer et al., 1980). By 1983 the process to produce fuel quality engine-tested biodiesel was completed and published internationally (Hawkin et al., 1983). An Austrian Company, Gaskoks, obtained the technology from the South African Agricultural Engineers and put up the first pilot plant for biodiesel in November, 1987, and the erection of the first industrial biodiesel plant on 12 April 1989, with a capacity of 30,000 metric tons of rapeseed per year. Throughout the 1990s, plants were opened in many European countries, including the Czech Republic, France, Germany, and Sweden. At the same time, nations in other parts of world also saw local production of biodiesel starting up and by 1998, the Austrian Biofuels Institute identified 21 countries with commercial biodiesel projects.

In the U.S., much of the impetus for the development of biodiesel has come from soybean farmers, who see it as a potential new market for soybean oil. In March 1992, a trade group of soybean farmers formed the National Soy Fuels Advisory Committee to investigate whether a potential market existed for biodiesel. This committee commissioned a study that concluded there were several large potential markets. The National Soy Fuels Advisory Committee then disbanded and a new, not-for-profit corporation, the National Soydiesel Development Board (NSDB), was formed in October, 1992, with the objective of commercializing biodiesel. To broaden their support from other feedstock groups, the NSDB subsequently changed its name to the National Biodiesel Board (NBB). The NBB was initially funded by a grant from the United Soybean Board, which received funding from check-off funds paid by soybean farmers across the country and by dues paid by board members. One-half percent of the selling price of every bushel of soybeans sold in the U.S. is collected through the USDA and made available to state and national farmer-run soybean associations for projects to enhance the soybean industry. At the national level the United Soybean Board receives the funds and the American Soybean Association provides administrative support. The NBB coordinated and financed much of the biodiesel-related research during the 1990s. This research culminated in the Health Effects testing needed to comply with the Environmental Protection Agency's Fuel and Fuel Additives Registration program.

The University of Idaho, assisted by the Idaho Energy Division and the Department of Energy Regional Bioenergy program sponsored three biodiesel commercialization conferences, in 1994, 1996, and 1997. These conferences were planned to consider three of most important considerations for future adoption of biodiesel: engine warranties, environmental issues, and fuel quality. The conferences were followed up with the National Renewable Energy Laboratory and NBB-sponsored research priority workshops.

The mission of the NBB, as stated on their web site is, "...to advance the interests of its members by creating sustainable biodiesel industry growth. NBB serves as the industry's central coordinating entity and will be the single voice for its diverse membership base. Industry growth will be achieved through public affairs, communications, technical, and quality assurance programs. We are dedicated to inclusiveness and integrity."

In 1995, Kenlon Johannes, J. A. Weber, and S. Howell submitted a report to the National Biodiesel Board entitled "1996-1998 Biodiesel Marketing Plan" (Schumacher et al., 1996). Schumacher et al. (1996) state "As early as four years ago [1992] there were only a few entities conducting research on biodiesel in the United States." They describe the coordinated approach to research and the development of a marketing plan by NBB. This consisted of a three-step plan to develop biodiesel in the U.S.: (1) The breakdown of research and development needs by specific niche markets, such as marine, regulated fleets, mining, urban buses, etc.; (2) The use of a logical, step-wise approach to funding and development of each market; (3) The use of industry-wide task forces to provide input and guidance for each specific market. These included engine manufacturers, biodiesel users, industry trade associations, biodiesel suppliers, research organizations, and regulatory authorities. The biodiesel research community as well as NBB recognized early that there was a need for a biodiesel quality standard. Because of the variability in research data and reporting styles, the ASAE Food and Processing Engineering (FPE) 709 Committee recognized the need for standardized data and developed an engineering practice, ASAE EP552 Reporting of Fuel Properties When Testing Diesel Engines with Alternative Fuels Derived from Biological Materials, which was first approved in 1996 and re-affirmed in 2001. The purpose of the Engineering Practice was "to establish a minimum set of fuel properties which should be included with the report of diesel engine performance on any oil derived from biological materials, including blends of these oils with diesel fuel." Following EP 552 facilitates comparison of test data between researchers.

Two other important developments were the development of a 200-Hour Screening Test for Alternate Fuels (NAEC, 1982) through joint efforts of Northern Agricultural Energy Center (NAEC; a subgroup of the USDA), engine manufacturers, and fuel additive suppliers, and a test to rapidly measure injector fouling in diesel engines (Korus and Jo, 1985). Both of these tests encouraged uniformity in test methods and procedures.

Schumacher et al. (1996) described the earliest U.S. quality standard that has since then evolved into ASTM D 6751, which was approved in 2002. Steve Howell, of NBB and Mark IV Consulting, chaired an ASTM subcommittee on biodiesel that developed the standard for biodiesel fuel. The standard continues to evolve and is now being balloted for a sixth version with several additions and refinements to meet the needs of newer engines and their fuel and emission systems, to provide consistency with European Specification EN14214, and to continue to assure biodiesel is a quality product suitable for use in modern diesel engines. ASTM D 6751 is a standard for 100% biodiesel intended for blending with diesel. The industry is currently working on a standard for B20 (20% biodiesel-80% diesel) that they believe will be a major factor in obtaining favorable consideration of the engine manufacturers for use of B20. Since 1996, the continuous efforts of the NBB assisted by many other state and local entities, such as state energy offices, clean cities organizations, and others, to promote and develop the industry has resulted in a significant increase in biodiesel use.

In accordance with requirements for fuel registration under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) ruled that biodiesel had to comply with Tier 1 and Tier 2 of the Act. In 2000, biodiesel, through the efforts of the NBB, was the first fuel to complete the health effects testing required by Tier 2, at a cost in excess of $2 million. Members of the NBB are allowed to use these data in their individual registration applications to the EPA. Nonmembers are also allowed to access the data but at a cost such that no biodiesel producer has become registered since the implementation of the health effects data requirement without first becoming a NBB member. Anyone wishing to sell biodiesel commercially must show evidence of complying with the requirements of the Clean Air Act and they have only been able to do this by joining the NBB.

By September of 2006 the NBB reported that over 500 million gallons (1.9 billion liters) of biodiesel production potential has been built in the U.S. and another 1.4 billion gallons (5.3 billion liters) of capacity is under construction (NBB, 2006).

Who Coined the Word "Biodiesel"?

Another historical point of interest is the origin of the term "biodiesel." It was not used in the proceedings of the 1982 ASAE conference, thus we can assume that it came about after that conference. In the conference proceedings, the closest terms are "Bio-Oils" used by Graeme Quick in the Preface and "Diesol" used in an undated reference to Cochran et al. We have in our possession a flyer from Bio-Energy (Australia) Pty. Ltd. that promotes equipment to produce "Low Cost Diesel Fuel" called "Bio-Diesel." Unfortunately, this flyer is not dated. The flyer was found attached to a letter to Graeme Quick that uses the word "Bio-Diesel." The letter is also not dated. However, three other documents that were found with these two are dated 1984. The first of these is a smaller flyer suggesting equipment for producing "Bio-Fuel" and the second is an article by

Graeme Quick for the Department of Agriculture in New South Wales, dated March 1984, that discusses the production of methyl and ethyl esters for engine fuel. He does not use the word "biodiesel" in that article. The third is an article for *Power Farming Magazine*, dated 1984, which states, "...the two fuels, BioDiesel and distillate, are virtually identical..." (Power Farming Magazine, 1984). We believe this is the earliest known use of the word "biodiesel." Knothe (2005b) reports that his search yielded a Chinese paper published in 1988 (Wang, 1988) that used the term "biodiesel," although this may have been the result of a later translation of a Chinese phrase, and that the next earliest paper appeared in 1991 (Bailer and de Hueber, 1991).

In a review paper for the ASAE, "Vegetable Oil as a Diesel Fuel—Status and Research Priorities," by Peterson (1985), the word "biodiesel" was not used either within the paper or in any of the references and that was still the case when Peterson (1991) prepared a summary article for an ASME conference entitled "Technical Overview of Vegetable Oil as a Transportation Fuel." In the proceedings of the Third Liquid Fuels Conference sponsored by ASAE in 1996, the earliest use of the word "biodiesel" in the title of a citation was 1991 (Worgetter et al., 1991, cited in Prankl and Worgetter, 1996) and in a 1991 article by Bill Freiberg in *Ag Biotechnology News* entitled "The Truth about Biodiesel—An Opportunity for Entrepreneurs." We assume that the use of "biodiesel" to describe esters of vegetable oils and animal fats was coined about 1984, was in limited use up to 1991, and became generally accepted after that date.

The term "biodiesel" was in fairly common use at the time of the establishment of the National Soydiesel Development Board (NSDB) in 1992. In the beginning, the NSDB called their fuel "Soydiesel" because their efforts were primarily sponsored by soybean farmers though the check-off system. In 1993, Midwest Biofuels, Inc. submitted a final report to the National Biodiesel Board entitled "Biodiesel Cetane Number Engine Testing—Comparison to Calculated Cetane Index Number," indicating that the National Soydiesel Development Board had by then changed their name and that "biodiesel" was becoming common terminology. As Knothe (2005b) has observed, after 1991 the use of the word "biodiesel" expanded exponentially. Who actually used it first is still open for speculation.

Biodiesel in Yellowstone National Park

One of the premier tests with biodiesel and one that probably provided more national exposure to biodiesel than any other demonstration was a test in Yellowstone National Park using 100% biodiesel in a Cummins-powered Dodge pickup. Howard Haines of the Montana Department of Environmental Quality coordinated this test with support from the Pacific Northwest and Alaska Regional Bioenergy Program and the States of Montana and Wyoming. The biodiesel consisted of ethyl esters of mustard oil and canola produced by the University of Idaho. This test program is summarized in a SAE paper (Taberski et al., 1999).

Biodiesel Historical Milestones

1900	Diesel engine demonstrated on peanut oil at the Paris Exhibition
1912	Rudolph Diesel suggests use of vegetable oils may be important for fuel.
1937	Belgian Patent 422,877 granted to G. Chavanne for using esters of vegetable oils as motor fuels
1938	Urban bus fueled with esters of palm oils operates between Brussels and Leuven
1938	Walton reports on "The Fuel Possibilities of Vegetable Oils"
1942	Seddon paper on "Vegetable Oils in Commercial Vehicles"
1942	Chowhurry et al. report on Indian vegetable oil as fuels for diesel engines
1947	Chang and Wan report on using tung oil for motor fuel in China
1951-1952	Two theses at Ohio State University, "Dual Fuel for Diesel Engines Using Cottonseed Oil with Variable Injection Timing" and "Dual Fuel for Diesel Engines Using Corn Oil with Variable Injection Timing"
1980	Bruwer et al. from South Africa report on utilization of sunflower seed oil as a renewable fuel for diesel engines includes tests with esters of sunflower oils
1981	North Dakota "Flower Power" project begins
1984	Wagner, Clark, and Schrock article "Effects of Soybean Oil Esters on the Performance, Lubricating Oil and Wear of Diesel Engines" and Geyer, Jacobus, and Lestz article "Comparison of Diesel Engine Performance and Emissions from Neat and Transesterified Vegetable Oils"
1984	Bio-Energy (Australia) Pty. Ltd. advertises equipment for producing "Bio-Diesel"
1988	Wang (China) article on " Development of Biodiesel Fuel"
1991	Worgetter describes "Project Biodiesel"
1991	Freiberg, "The Truth About Biodiesel —An Opportunity for Entrepreneurs" published in *Ag Biotechnology News*
1992	National Soydiesel Development Board (NSDB) organized
1994	NSDB becomes the National Biodiesel Board (NBB)
1994	University of Idaho completes coast-to-coast and back on-road test with 100% biodiesel fueling a Cummins-powered Dodge pickup
1994	Conference on "Commercialization of Biodiesel: Establishment of Engine Warranties" sponsored by the University of Idaho, Moscow, Idaho
1995	Yellowstone National Park Biodiesel Project begins
1996	Conference on "Commercialization of Biodiesel: Environmental and Health Effects" at Mammoth Hot Springs, Yellowstone National Park
1997	Conference on "Commercialization of Biodiesel: Producing a Quality Fuel" at Boise, Idaho
1998	Beginning of Kenworth/Caterpillar Simplot 200,000-mile test with HySEE biodiesel in a heavy-duty truck
1998	CCC buy-down program for producers of biodiesel
2000	Biodiesel passed Tier 2 health effects testing requirements of the Clean Air Act through efforts of NBB
1999	Biodiesel production surpasses 0.5 million gallons
2000	Biodiesel production surpasses 2 million gallons
2002	ASTM Standard D-6751 for Biodiesel approved
2004	American Jobs Creation Act provides a federal subsidy of $1 per gallon for biodiesel fuels made from virgin oils and $0.50 per gallon for other biodiesel fuels.
2006	Two billion gallons of biodiesel production capacity in the U.S. either completed or under construction

The University of Idaho produced, tested, and delivered the biodiesel, and supplied the technical assistance for all the testing, including performance and emissions testing that was used by the EPA to determine emissions reductions. The truck was donated by Dodge Truck.

The initial questions regarded emissions, potential for bear attraction, and cold climate, because of questions by National Park Service staff in Washington, D.C., who had refused a project proposed by NBB because of a potential increase in emissions in Grand Canyon National Park. Approval was gained for the Yellowstone project because it included testing for fuel quality and emissions (Haines, 2006). Biodiesel is now used in more than 50 units of the National Park System nationwide.

200,000 Mile Over-the-Road Test with a Heavy-Duty Truck Using HySEE

The 200,000-mile (333,000-km) over-the-road test was a unique project started in 1998 that involved industry, government, and university personnel. Biodiesel was produced from used vegetable oil from a potato processing plant (J. R. Simplot Co., Caldwell, Idaho) using ethanol produced from potato waste. The fuel was named "HySEE," which denotes *hydrogenated soybean ethyl ester*. The fuel was used to power a large, heavy-duty Kenworth truck powered with a Caterpillar engine. Kenworth supplied the truck, Caterpillar supplied two engines, and J. R. Simplot Co. operated the truck. One of the two Caterpillar engines was used to power the truck; the other was used for emissions testing in accordance with EPA 211(b) fuel registration requirements. Funding for the project was initiated by the efforts of the Pacific Northwest and Alaska Regional Bio-Energy program of the DOE and the Energy Division of the Idaho Department of Water Resources. Western States Caterpillar of Boise, Idaho, dyno-tested the truck at regular intervals; Caterpillar, Inc., conducted the startup and emissions testing; and the University of California-Davis conducted the chemical and biological assay work. The University of Idaho coordinated the project and prepared the fuel. The fuel used was a 50% blend of HySEE biodiesel and diesel fuel. The demonstration vehicle traveled 202,160 miles (336,933 km) averaging 5.27 miles/gallon (2.3 km/liter). To the knowledge of the participants it was the first operational demonstration utilizing advanced diesel fuel injection technology: Caterpillar electronic unit fuel injectors. Results of wear measurement testing suggested that this engine could be expected to exceed a vehicle mileage of 1 million miles (1,667,000 km). In Caterpillar's report, "Nearly all aspects of the test passed evaluation with flying colors" (Chase et al., 2000).

Fundamentals of Biodiesel Chemistry

Biodiesel is produced through a process known as transesterification. This is a chemical process whereby an ester is reacted with an alcohol to form another ester and another alcohol. In the case of biodiesel, the reaction is shown below, where R_1, R_2, and R_3 are long hydrocarbon chains, sometimes called fatty acid chains.

Triglyceride   **Methanol**   **Mixture of fatty esters**   **Glycerin**
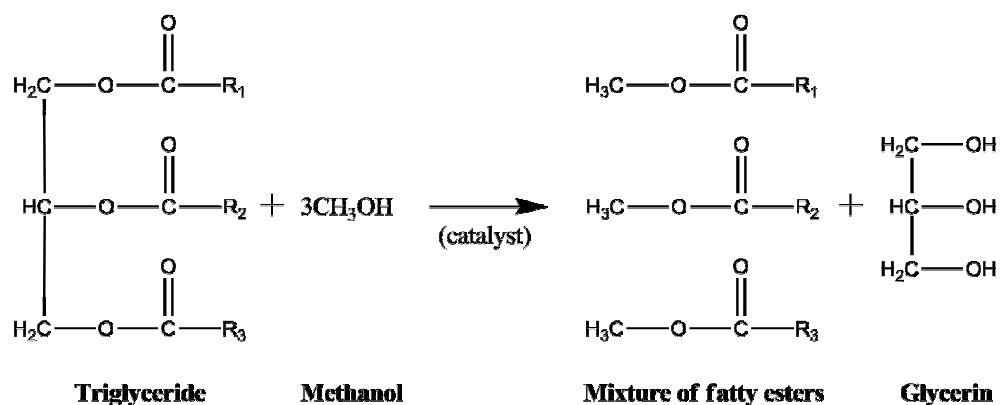
There are five chains that are most common in soybean oil and animal fats (others are present in small amounts). As shown in the reaction diagram, the triglyceride contains three separate ester functional groups so it can react with three molecules of methanol to form three molecules of methyl ester and glycerol, which is a tri-alcohol. The catalyst for this reaction is usually a strong base such as sodium or potassium hydroxide. These hydroxides cause the methanol to dissociate and produce the methoxide ion, which is the actual catalytic agent. Most producers prefer to use sodium methoxide concentrate, which can be purchased as a liquid and which does not contain the water that is created when hydroxides are used to produce the methoxide.

Transesterification is a well-known reaction in organic chemistry. The industrial-scale processes for transesterification of vegetable oils were initially developed in the early 1940s to improve the separation of glycerin during soap production (Bradshaw, 1942; Bradshaw and Meuly, 1942).

All vegetable oils and animal fats consist primarily of triglycerides (also known as triacylglycerols). Triglycerides have a three-carbon backbone with a long hydrocarbon chain attached to each of the carbons. These chains are attached through an oxygen atom and a carbonyl carbon, which is a carbon atom that is double-bonded to a second

oxygen. The differences between oils from different sources relate to the length of the fatty acid chains attached to the backbone and the number of carbon-carbon double bonds on the chain. Most fatty acid chains from plant and animal based oils are 18 carbons long with between zero and three double bonds. Fatty acid chains without double bonds are said to be *saturated* and those with double bonds are *unsaturated*. Table 1 shows the amount of each of the five common fatty acid chains found in common oils and fats.

The presence of double bonds in the fatty acid chains has a dramatic effect on the properties of the methyl esters. The deformation of the molecule caused by the double bonds inhibits the growth of the crystals and this lowers the biodiesel's gel temperature. Saturated fats tend to gel at higher temperatures. Animal fats, hydrogenated vegetable oils, and some tropical oils such as palm oil and coconut oil contain 35% to 45% saturated fatty acids and may be solid at room temperature. Biodiesel produced from these oils may gel at unacceptably high temperatures.

The carbon-carbon double bonds in unsaturated oils and fats are prone to oxidation by oxygen in the air. This effect is magnified when the bonds are conjugated (two double bonds separated by two single bonds), as is the case for

Table 1. Fatty acid composition for common oils and fats (% by weight) (Van Gerpen et al., 2006).

	Palmitic acid	Stearic acid	Oleic acid	Linoleic acid	Linolenic acid
Number of carbons	16	18	18	18	18
Number of double bonds	0	0	1	2	3
Soybean	8	4	25	55	8
Canola (high oleic acid rapeseed)	4	2	60	22	12
High erucic acid rapeseed[a]	3	1	13	14	10
Mustard oil[b]	4	2	24	21	10
Olive oil	10	2	78	10	trace
Palm oil	44	5	40	10	trace
Tallow[c]	28	22	42	4	trace
Lard	28	15	45	11	1
Yellow grease	20	18	54	8	trace

[a] High erucic acid rapeseed can have up to 15% gadoleic (eicosenoic) acid (C20:1) and 50% erucic acid (C22:1).
[b] Mustard oil typically contains 12% gadoleic (eicosenoic) acid and 25% erucic acid.
[c] Tallow typically has 3% to 6% myristic acid (14 carbons, no double bonds)
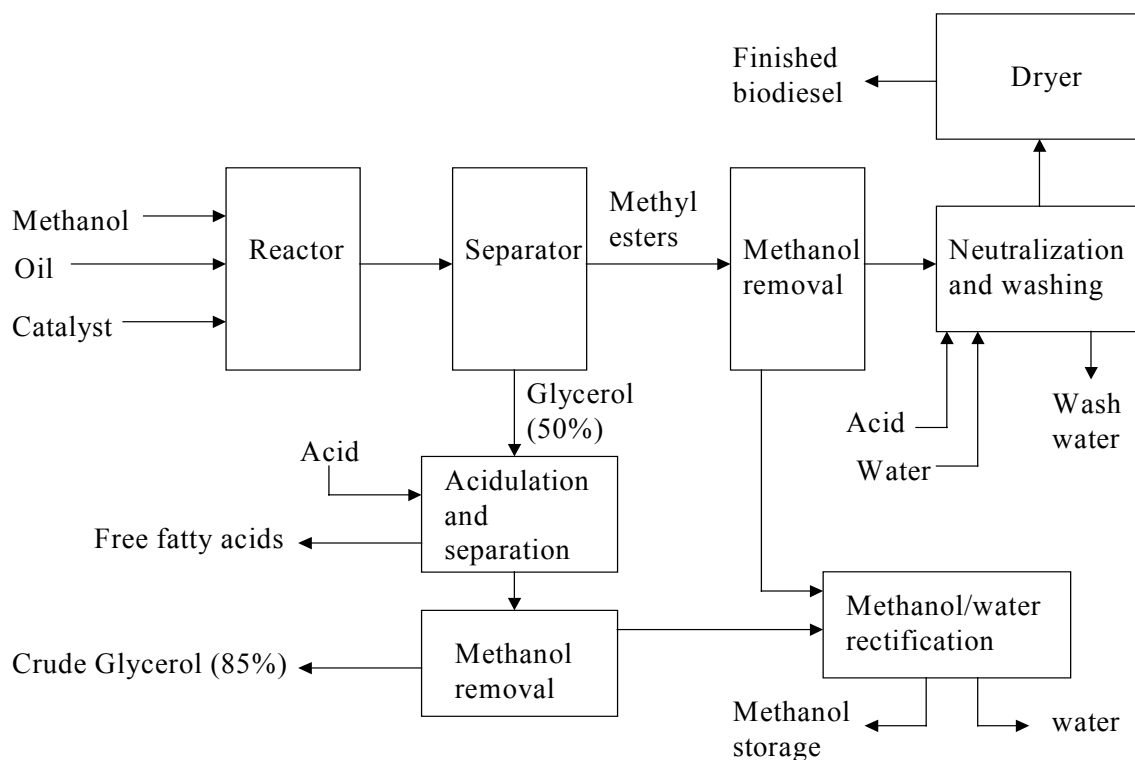
Figure 1. Schematic of biodiesel processing.

linoleic and linolenic acids. These fatty acids will oxidize 50 to 100 times faster than oleic acid with an unconjugated double bond (Knothe, 2005c). Saturated fatty acids are not subject to this type of oxidative attack.

The choice of oil or fat feedstock determines the resulting biodiesel's position in the trade-off between cold flow, oxidative stability, and cetane number. Biodiesel from more saturated feedstocks will have higher cetane numbers and better oxidative stability, but will have poor cold flow properties. Biodiesel from oils with low levels of saturated fats will have better cold flow properties, but lower cetane number and oxidative stability (Dunn, 2005; Knothe, 2005a).
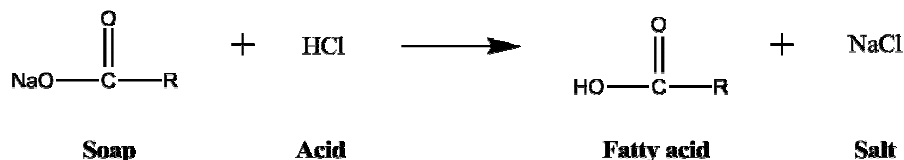
Biodiesel Processing

Figure 1 is a schematic of the biodiesel production process (Van Gerpen, 2005). The primary input is assumed to be oil that has previously been extracted from an oilseed such as canola or soybean. To accomplish the transesterification reaction described above, the oil, methanol, and catalyst are mixed together in a stirred reactor. Higher temperatures will cause the reaction to reach equilibrium more rapidly, but in most cases the temperature is kept below the normal boiling point of the methanol so the reactor does not need to be pressurized. As shown in the reaction equation described earlier, three moles of methanol react with one mole of triglyceride. In practice, most producers will use at least 100% excess methanol (6:1 molar ratio) to force the

reaction equilibrium towards a complete conversion of the oil to biodiesel.

The reaction is slowed by mass transfer limitations since at the start of the reaction the methanol is only slightly soluble in the oil and later on, the glycerin is not soluble in the methyl esters. Since the catalyst tends to concentrate in the glycerin, it can become unavailable for the reaction without agitation. A common approach to overcome this issue is to conduct the transesterification in two stages. First, the oil is combined with 75% to 90% of the methanol and catalyst and this mixture is allowed to react to equilibrium. Then, the glycerin that has formed is separated and the remaining 10% to 25% of the methanol and catalyst is added for a second reaction period. At the conclusion of this second reaction period, the remaining glycerin is separated and the biodiesel is ready for further processing. The glycerin separation steps are usually accomplished by gravity settling or with a centrifuge.

The glycerin that is separated from the biodiesel will contain a substantial amount of methanol, most of the catalyst, soaps that have been formed during the reaction, and many of the polar contaminants that were originally present in the oil. These contaminants contribute to a dark brown or black color for the glycerin in spite of it being clear when present as a pure compound. The raw glycerin has very little value and must be upgraded to raise its purity before it can be sold. The usual practice is to add a strong acid to the glycerin to neutralize the catalyst and split the soaps. The soaps split into free fatty acids (FFAs) and salt, as shown in the following equation.

$$\text{NaO}\!-\!\overset{\displaystyle O}{\overset{\|}{C}}\!-\!R \quad + \quad HCl \quad \longrightarrow \quad \text{HO}\!-\!\overset{\displaystyle O}{\overset{\|}{C}}\!-\!R \quad + \quad NaCl$$

Soap   **Acid**   **Fatty acid**   **Salt**

The FFAs are not soluble in the glycerin and will rise to the top in a decanter or can be separated with a centrifuge. The methanol can be removed by vaporization leaving a crude glycerol that is 80% to 90% pure. Most of the impurities will be salts. Only a few of the biodiesel producers in the U.S. have invested in the equipment to refine this crude glycerin to the 99.5% purity required for pharmaceutical and cosmetic applications.

For every 100 kg (220 lb) of oil that is converted to biodiesel, there is about 10.5 kg (23.1 lb) of glycerol produced. The glycerol produced by biodiesel production is beyond that needed to meet the existing demand and recent prices for United States Pharmacopeia (USP) grade kosher glycerin are only a third to half of historical averages. Glycerol is a disposal problem for many biodiesel producers. New uses for this excess production of glycerin are being developed, such as animal feed, composting accelerant, antifreeze (Suppes et al., 2005), and as a deicing/anti-icing agent (Sapienza et al., 2005).

After the biodiesel is separated from the glycerol, it contains 3% to 6% methanol and usually some soap. If the soap level is low enough (300 to 500 ppm), the methanol can be removed by vaporization and this methanol will usually be dry enough to directly recycle back to the reaction. Methanol tends to act as a cosolvent for soap in the biodiesel, so at higher soap levels the soap will precipitate as a viscous sludge when the methanol is removed.

After the methanol has been removed, the biodiesel needs to be washed to remove residual free glycerin, methanol, soaps, and catalyst. This is most frequently done using liquid-liquid extraction by mixing water with the biodiesel and gently agitating them to promote the transfer of the contaminants to the water without creating an emulsion that might be difficult to break. The washing process is usually done multiple times until the wash water no longer picks up soap. Although the graywater from later washes can be used as the supply water for the earlier wash steps, the total amount of water will typically be one to two times the volume flow rate of the biodiesel.

Sometimes, to reduce the amount of water required, producers will add acid to the wash water. Weaker organic acids, such as citric acid, will neutralize the catalyst and produce a soluble salt. Stronger inorganic acids, such as hydrochloric, sulfuric, or phosphoric, can be used to split the soap and this reduces the water requirement to 5% to 10% of the biodiesel flow because the salts are easier to remove than the soap. After washing, the biodiesel is frequently cloudy due to small water droplets suspended in the fuel. While these droplets will eventually settle out, it is much faster to use a flash evaporator to remove the residual water from the fuel.
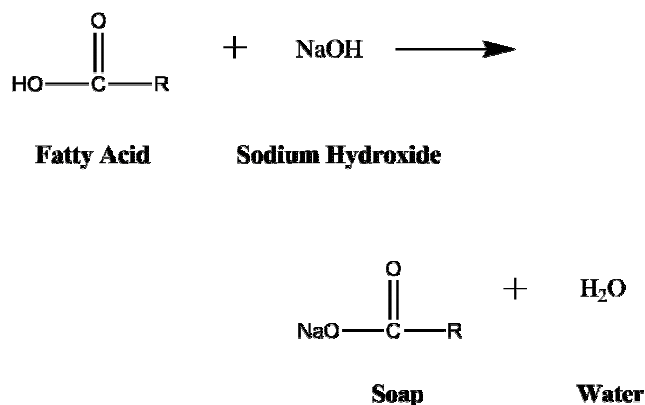
Alternatives to water washing that use solid absorbents, such as magnesium silicate, have been developed. This material is supplied as a fine powder that is added after methanol removal. The powder adsorbs the polar contaminants such as soap, catalyst, and free glycerol and after filtering leaves a clean, dry product. This approach eliminates water from the process and removes the risk of emulsion formation during washing, which is a constant concern with water washing. Other products, such as ion-exchange resins, can also remove soap and contaminants and some can be used without prior removal of methanol.

Processing Low-Cost Feedstocks

The higher price of biodiesel has caused many researchers to look for ways to reduce its cost. Since 75% to 80% of the production cost of biodiesel is the cost of the oil or fat, to produce a fuel that is competitive with diesel fuel requires a low-cost feedstock (Van Gerpen et al., 2006). These feedstocks are available, but they usually contain contaminants that make them undesirable for food use. The most important contaminants are free fatty acids. These organic acids are the products of hydrolysis reactions that split the fatty acid chains from the original oil or fat. Restaurant waste oils typically contain 2% to 4% free fatty acids while rendered animal fats can exceed 25% to 30%. The oil portion of the waste collected from restaurant grease traps can be as high as 100% free fatty acids. The free fatty acids contribute to undesirable smells and flavors in the oil so when their level exceeds about 1%, the oil is no longer considered edible.

These high free fatty acid oils present special challenges when used for biodiesel production. When an alkali catalyst is added to these feedstocks, the free fatty acid reacts with the catalyst to form soap and water as shown in the reaction below.

$$\text{HO}\!-\!\overset{\displaystyle O}{\overset{\|}{C}}\!-\!R \quad + \quad NaOH \quad \longrightarrow$$

Fatty Acid   **Sodium Hydroxide**

$$\text{NaO}\!-\!\overset{\displaystyle O}{\overset{\|}{C}}\!-\!R \quad + \quad H_2O$$

Soap   **Water**

This reaction makes the catalyst unavailable for catalyzing the reaction and if enough soap is produced it can inhibit the separation of the methyl esters and glycerin.

When oils and fats with high free fatty acids are to be used for biodiesel production, an acid catalyst such as sulfuric acid can be used to esterify the free fatty acids to methyl esters as shown in the following reaction.

Fatty Acid   **Methanol**
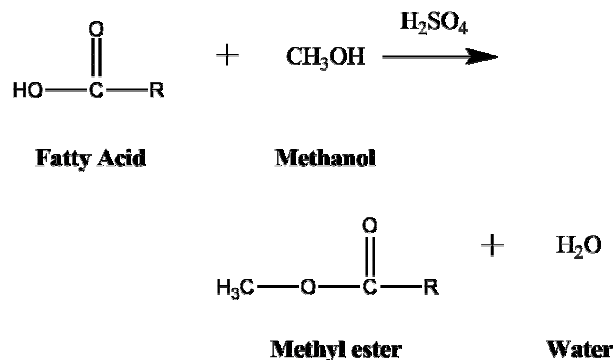
Methyl ester   **Water**

Then, with the FFAs converted to methyl esters, a conventional alkali-catalyzed process can be used to transesterify the triglycerides in the feedstock. While acids can be used to catalyze the transesterification reaction, the reaction is very slow at the 50° to 60°C reaction temperature (Canakci and Van Gerpen, 1999). The two-step approach of acid-catalyzed esterification followed by base-catalyzed transesterification gives a complete reaction at moderate temperatures (Keim, 1945; Canakci and Van Gerpen, 2001, 2003). A problem with this approach is that the water produced by the esterification reaction should be removed before the base-catalyzed process begins so that soap formation is not excessive. This can be done by settling or centrifuging the methanol-water-acid layer that separates after the esterification has reached equilibrium (Canakci and Van Gerpen, 2001). The additional equipment required for the acid-catalyzed pretreatment raises the processing cost, but this approach allows the use of feedstocks containing up to 100% FFA. A similar approach has been used to produce biodiesel from soapstock, a waste product of the soybean oil refining process (Haas et al., 2000; 2002; Haas, 2005).

As the biodiesel industry grows, new production technologies are considered and those that provide competitive advantages are adopted. These include a change from the current homogeneous catalysts, where the catalyst is dissolved in the reactants and must be removed after the reaction, to heterogeneous catalysts that can be implemented as packed beds through which the oil and alcohol would flow and have clean biodiesel and glycerin emerge. Several heterogeneous catalyst technologies are being proposed for biodiesel production (Ilankumaran and Verkade, 1999; Stern et al., 1999; Mbaraka et al., 2003; Mbaraka and Shanks, 2005), but those currently available for industrial use require high temperature and pressure. The high energy requirement is comparable to a non-catalytic approach that uses methanol at supercritical conditions (T > 250ºC) to achieve complete reaction (Saka and Dadan, 1999; Kusdi-

ana and Saka, 2001; Saka and Kusdiana, 2001). These approaches have not yet found wide acceptance in the U.S., but the use of heterogeneous catalysts, which are widespread in the petrochemical industry, is the subject of intense research.

Another production alternative uses a co-solvent to make the alcohol-oil-methyl ester-glycerin system a single phase (Boocock et al., 1994, 1996, 1998). By choosing a co-solvent such as tetrahydrofuran that has a boiling point that is close to that for methanol, the co-solvent can be recovered and recycled with the methanol. This technology, while providing the advantage of shorter reaction time, has only been implemented in a single plant in North America.

Biodiesel Utilization

Energy Balance

As a guide for policy, researchers have developed an analysis procedure called Life Cycle Analysis (LCA). This technique tracks all of the energy required to produce a fuel and compares it to the energy contained in the fuel. Because solar energy is typically excluded from the calculations, the LCA of bio-based fuels usually shows that the fuel contains more energy than the energy required to produce it. A careful study conducted by the National Renewable Energy Laboratory (NREL) and the USDA showed that the energy in soy-based biodiesel was 3.2 times greater than the energy required to produce it (Sheehan et al. 1998). LCA can also provide estimates of total pollutant formation and the NREL/USDA study showed that biodiesel results in 78% less CO_2 released to the atmosphere. A recent study (Pimentel and Patzek, 2005) received extensive press coverage when it claimed that biodiesel actually required more energy to produce than was contained in the fuel. The Pimentel study has since been shown to contain numerous errors, which when corrected, gives a conclusion that is similar to the earlier NREL/USDA study (Van Gerpen and Shrestha, 2005). Other crops may have higher or lower energy balance figures than soybeans depending on agricultural factors such as fertility, crop establishment requirements, harvesting and processing energy, etc.

Biodiesel Blends

Biodiesel will blend with petroleum diesel in any proportion. Three specific blends are of special interest. B2 contains 2% biodiesel in 98% petroleum diesel. Similarly, B20 contains 20% biodiesel and B100 contains 100% biodiesel. B2 is of interest because of its lubricity benefits. B20 helps reduce engine emissions in addition to improving fuel lubricity. B100 provides both benefits and also provides complete replacement of petroleum diesel if the biodiesel could be supplied in sufficient amounts at an affordable cost.

B2 Lubricity Benefits

Lubricity can be defined as the ability of a liquid to provide hydrodynamic and/or boundary lubrication to prevent wear between moving metal parts. Hydrodynamic lubrication occurs when the oil film is sufficiently thick to prevent

any metal-to-metal contact between parts moving relative to one another. When the oil film is very thin, i.e., the approximate thickness of a single molecule, the lubrication is termed *boundary lubrication*. Having the oil film thicker than one molecule but not thick enough for hydrodynamic lubrication is termed *mixed-film lubrication*. The oiliness of the lubricant is very important in boundary lubrication. *Oiliness* refers to the ability of the lubricant to adhere to metal surfaces. Biodiesel consists of fatty acid esters and such esters have excellent oiliness (Goering et al., 2003). An ester molecule can be viewed as an ester head with a hydrocarbon tail. The polarity of the ester head causes it to adhere to metal surfaces, thus providing excellent oiliness. Knothe and Steidley (2005) have shown that much of biodiesel's lubricity may be due to the presence of small amounts of contaminants in the fuel such as free fatty acids and monoglycerides.

In a compression ignition (CI) engine, the engine oil lubricates the engine, but the fuel must provide lubrication for most fuel injection systems. Rotary and distributor-type injection pumps are especially susceptible to boundary lubrication wear (LePera, 2000). The Engine Manufacturer's Association (EMA) has specified that a minimum SLBO-CLE (Scuffing Load Ball on Cylinder Lubricity Evaluator) lubricity of 3,100 g (6.82 lb) is required to protect the fuel injection system. In this test, a stationary steel ball bearing is pressed against the end of a rotating cylinder that is partially immersed in the lubricity fluid. Loading is increased on the ball until a scuff mark appears on the cylinder. The ball loading in grams is used as the measure of lubricity, with higher numbers indicating greater lubricity. The SLBOCLE test procedure has been standardized by ASTM (1999a) as D 6078.

The EMA also specifies a HFRR (High Frequency Reciprocating Rig) rating of 450 µm (0.0177 in.) or less to protect the injection system. In the HFRR test, a computer controls a ball sliding with reciprocating motion (1 mm stroke) on a flat specimen coated with the lubricant while a 200 g (0.44 lb) load is applied to the ball. After 75 minutes, a 100X microscope is used to measure the average diameter of the wear scar that has been worn on the ball. The average diameter of the wear scar, in µm, is used as the measure of lubricity with smaller numbers indicating greater lubricity. The HFRR test procedure has been standardized by ASTM (1999b) as D 6079.

The SLBOCLE test is best suited for fuels that may contain lubricity additives. The HFRR test does not work well for fuels containing small amounts of lubricity-enhancing additives. Also, much of the variability in SLBOCLE test results is associated with operator technique, whereas the HFRR results are less dependent on operator technique. The fuel injection equipment manufacturers have adopted the use of the HFRR test and recommend that diesel fuel

should produce a HFRR scar diameter of 460 µm (0.0181 in.) or smaller (Delphi Diesel Systems et al., 2000) and a HFRR requirement has recently been added to the ASTM specification for diesel fuel, ASTM D 975 (ASTM, 2006).

Prior to 1993, petroleum diesel provided sufficient lubricity to protect the injection system of a CI engine. In that year, the EPA mandated that the sulfur content of diesel fuel must not exceed 500 ppm, compared to the previous limit of 5,000 ppm. The sulfur reduction was needed to reduce exhaust emissions, but removing the sulfur also reduced the fuel lubricity (Barbour et al., 2000). In a study conducted at Iowa State University (Van Gerpen et al., 1998), blending biodiesel with No. 2 petroleum diesel increased the fuel lubricity, as shown in Table 2. The addition of 1% biodiesel was sufficient to achieve the minimum required lubricity for No. 1, low-sulfur diesel fuel. No. 2 low-sulfur diesel fuel exceeded the minimum required lubricity without the biodiesel additive but the 1% biodiesel improved the lubricity further.

Table 2. Lubricity test results for low-sulfur diesel fuel.

	No. 1 diesel		No. 2 diesel	
Additive	SLBOCLE	HFRR	SLBOCLE	HFRR
None	1250 g	675 µm	4150 g	376 µm
1% biodiesel	3700 g	294 µm	5000 g	251 µm

On 1 June 2006, the EPA lowered the allowable sulfur limit in diesel fuel to 15 ppm. The sulfur reduction will allow the use of after-treatment that reduces exhaust emissions by 90%. However, the accompanying reduction in fuel lubricity could cause diesel injection systems to fail. Table 3 shows the effect of various levels of biodiesel in restoring the lubricity of this ultra-low sulfur fuel (Schumacher, 2005). In this study, addition of either 1% or 2% biodiesel provided sufficient lubricity to ultra-low sulfur No. 2 diesel fuel (D2), but higher concentrations were needed to supply sufficient lubricity to No. 1 diesel fuel with ultra-low sulfur (D1). Interpolating the data suggests that 5% biodiesel additive would provide sufficient lubricity to No. 1 ultra-low sulfur diesel.

Some lubricity additives can cause adverse consequences if used at too high a dosage. An advantage of using biodiesel to improve the lubricity of petroleum diesel is that the biodiesel is itself a fuel. Biodiesel can be used in concentrations up to 100% without such adverse consequences.

B20 Emissions Improvements

Biodiesel has entered the marketplace at a time when the EPA is tightening emissions standards for compression ignition (CI) engines. Table 4 shows the schedule of emissions standards for off-road CI engines (Goering and Hansen, 2004). Emissions standards for on-road CI engines are also being tightened.

Table 3. SLBOCLE test results for various levels of biodiesel in ultra-low sulfur diesel fuel.

Fuel	B0	B0.5	B1	B2	B4	B12	B100
D1	1250 g	N/A	2550 g	2880 g	2950 g	4200 g	5450 g
D2	2100 g	2600 g	3400 g	3500 g	N/A	N/A	5450 g

Exhaust emissions from a CI engine are products of combustion. CI engine combustion occurs in two phases, as illustrated in Figure 2. This is a plot of the energy release rate from the fuel versus crankshaft angle. When fuel injection begins, there is an ignition delay during which the fuel is atomized and begins evaporating and mixing with air while certain pre-ignition reactions occur. Ignition occurs at the end of the ignition delay and the vaporized fuel that has premixed with air burns quite suddenly, resulting in the premixed combustion peak of Figure 2. Additional combustion occurs as the fuel and air mix. The diffusion combustion occurs more slowly than premixed combustion (Goering et al., 2003). The relative amounts of premixed and diffusion combustion vary depending upon engine load, injection timing, and the cetane rating of the fuel. As more fuel is injected per cycle with increasing load, the fuel injected after the end of premixed combustion burns in diffusion combustion; thus the percentage of diffusion burning increases with load. Advancing the start of injection increases the ignition delay, thus increasing the relative amount of premixed combustion. Higher cetane fuels have shorter ignition delays and thus less premixed combustion.

Reducing diesel engine emissions involves tradeoffs. NO_x emissions are highest when premixed combustion is high, where air and fuel are well mixed and cycle temperatures are highest. Carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) emissions are produced primarily in diffusion combustion, where air and fuel are not well mixed and combustion is less complete. Thus, engine adjustments that shift more of the combustion

Table 4. Air pollutant emission standards specified by the EPA for off-road compression ignition engines.

Rated Power (P_b) in kW(hp)	Tier	Year	CO (g/kWh)[b]	NMHC[a] (g/kWh)	NMHC + NO_x (g/kWh)	NO_x (g/kWh)	PM (g/kWh)
P_b <8.2(11)	Tier 1	2000	8.0		10.5		1.0
	Tier 2	2005	8.0		7.5		0.8
8.2(11)≤P_b<19(25)	Tier 1	2000	6.6		9.4		0.8
	Tier 2	2005	6.6		7.5		0.8
P_b<19(25)	Tier 4[c]	2008	6.6		7.5		0.4
19(25) ≤P_b<37(50)	Tier 1	1999	5.5		9.4		0.8
	Tier 2	2004	5.5		7.5		0.6
19(25) ≤P_b<56(75)	Tier 4	2013	5.0		4.7		0.03[d]
37(50) ≤P_b<75(100)	Tier 1	1998				9.3	
	Tier 2	2004	5.0		7.5		0.4
	Tier 3	2008	5.0		4.7		0.4
75(100) ≤P_b<130(175)	Tier 1	1997				9.3	
	Tier 2	2003	5.0		6.6		0.3
	Tier 3	2007	5.0		4.0		0.3
56(75) ≤P_b<130(175)	Tier 4	2012-2014[e]	5.0	0.19		0.40	0.02
130(175) ≤P_b<225(300)	Tier 1	1996	11.4	1.3		9.3	0.5
	Tier 2	2003	3.5		6.6		0.2
	Tier 3	2006	3.5		4.0		0.2
130(175) ≤P_b<560(750)	Tier 4	2011-2014[f]	3.5	0.19		0.40	0.02
225(300) ≤P_b<450(600)	Tier 1	1996	11.4	1.3		9.3	0.5
	Tier 2	2000	3.5		6.4		0.2
	Tier 3	2006	3.5		4.0		0.2
450(600) ≤P_b<560(750)	Tier 1	1996	11.4	1.3		9.3	0.5
	Tier 2	2002	3.5		6.4		0.2
	Tier 3	2006	3.5		4.0		0.2
P_b≥560 (750)	Tier 1	2000	11.4	1.3		9.3	0.5
	Tier 2	2006	3.5		6.4		0.2
P_b≥560 (750)	Tier 4	2011-2014[g]	3.5	0.19		0.40	0.02

[a] NMHC = non-methane hydrocarbons.
[b] Multiply standard by 0.7457 to convert from g/kW-h to g/ bhp-h.
[c] Proposed Tier 4 emissions standards to be phased in from 2008-2014.
[d] Interim PM standard of 0.30 g/kWh effective 2008.
[e] 2012-2013: full CO/PM compliance, 50% phase-in engines meet NO_x/HC (phase-out NMHC+NO_x < 4.0 g/kWh).
[f] 2011-2013: full CO/PM compliance, 50% phase-in engines meet NO_x/HC (phase-out NMHC+NO_x < 4.0 g/kWh).
[g] 2011-2013: full CO compliance, 50% phase-in engines meet NO_x/PM/HC (phase-out NMHC+NO_x < 6.4 g/kWh, PM < 0.20 g/kWh).
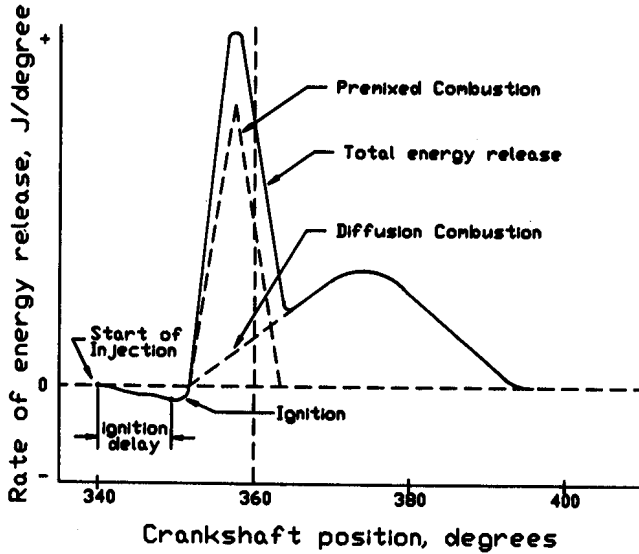
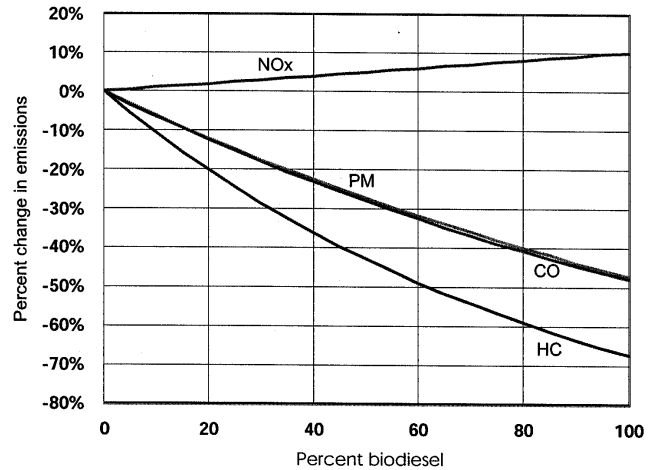**Figure 2. Schematic diagram of heat release in a compression ignition engine.**

Figure 3. Average impacts of biodiesel on exhaust emissions from heavy-duty highway engines (after Korotney, 2002).

into the diffusion burning mode tend to reduce NO_x emissions but increase CO, HC, and PM emissions, and vice versa.

Table 5 summarizes emissions changes that occurred when petroleum diesel fuel was replaced by B20 in transient engine tests. The results shown in the second column are average results from tests conducted at the Southwest Research Institute (SWRI) and the Colorado Institute for Fuels and High Altitude Engine Research (CIFER). Their results were from CFR 40 transient tests conducted using a DDC Series 60, six-cylinder, four-cycle, 12.7-liter turbocharged engine. (CFR 40 refers to a section of the Code of Federal Regulations governing transient emissions testing.) This engine was chosen as being typical of current on-road truck technology at the time and because it had been used extensively in emission studies (Schumacher, 1995). The data in column three of Table 5 are averaged results from a report by the EPA (Korotney, 2002) that drew on a variety of studies of unmodified engines (no timing adjustments).

As Table 5 illustrates, use of B20 to replace petroleum diesel fuel causes a reduction of total HC, CO, and PM emissions but a slight increase in NO_x emissions. Tat et al. (2004) found that the properties of biodiesel can cause an advance in the start of fuel injection. As noted above, advancing the start of injection increases the ignition delay and the relative amount of premixed combustion, thus

Table 5. Percentage changes in emissions when B20 was substituted for petroleum diesel. (Schumacher, 1995; Korotney, 2002)

Pollutant	SWRI and CIFER	EPA
Total HC	−12.8	−21.1
CO	−7.1	−11.0
NO_x	+1.1	+2.0
PM	−19.6	−10.1

increasing NO_x emissions. By readjusting the injection system to retard the start of injection, the small increase in NO_x emissions can be removed, but the normal reductions in HC, CO, and PM emissions observed with B20 will be somewhat diminished.

B100 Emissions

The EPA (Korotney, 2002) reviewed emissions research from a variety of tests of biodiesel and produced the graph shown as Figure 3. It shows average emission impacts from use of various concentrations of biodiesel in petroleum diesel. The CO, HC, and PM emissions continue to decline with increasing concentrations of biodiesel, while NO_x emissions continue to increase. Not shown in Figure 3 are the effects of biodiesel on emissions of sulfur oxides, which are harmful emissions. Biodiesel from vegetable oil has a low sulfur level, although biodiesel from certain rendered fats has occasionally been found to contain 50 to 200 ppm of sulfur. Thus, exhaust emissions should include very little sulfur oxides when B100 was used as the fuel. Sulfur oxide emissions generally increase with the concentration of petroleum diesel in the blend.

The same EPA study (Korotney, 2002) considered the effect of biodiesel on unregulated hazardous air pollutants, referred to as toxics in the report. They found no data on toxic metals (arsenic, chromium, lead, manganese, mercury, and nickel) but since biodiesel is free of these metals it would not contribute to their presence in diesel exhaust. On the basis of sparse data for 11 other toxics (acetaldehyde, acrolein, benzene, 1,3-butadiene, formaldehyde, n-hexane, naphthalene, styrene, toluene, and xylene), Korotney (2002) concluded that the impact of biodiesel on total toxics is beneficial. The data were too sparse to draw conclusions on individual toxic air compounds.

Petroleum Displacement and Global Warming

Emissions of CO_2 are of interest because of the likelihood that they contribute to global warming through the greenhouse effect. The EPA study (Korotney, 2002) did not

include data on engine emissions of CO_2. Rather, the EPA evaluated the hydrogen/carbon ratios of biodiesel and conventional diesel fuel. The data were corrected to reflect that biodiesel has a smaller heating value than conventional diesel. The results indicated that, on an equal energy basis, biodiesel has about 1% greater carbon content than conventional diesel. Thus, if two identical engines, one running on conventional diesel and the other on biodiesel, were compared on an equal work output basis, the one running on biodiesel would be expected to produce slightly more CO_2. However, the growing plants that produced the biodiesel would have withdrawn CO_2 from the environment in the recent past, thus reducing the net contribution of CO_2 to the environment. While petroleum was also developed from growing plants, that growth occurred eons ago and the carbon has been sequestered in the earth in the interim. Thus, when CO_2 is produced from combustion of conventional diesel fuel, there is no offsetting CO_2 capture associated with recently growing plants. If use of biodiesel produced no energy gain, (energy in the petroleum used to produce biodiesel was greater than that contained in the biodiesel) there would be no CO_2 reduction achieved from use of biodiesel. In fact, when the solar input to the growing plants is discounted, there is a net energy gain of 320% associated with biodiesel and a net reduction in CO_2 emission of 78% (Sheehan et al., 1998). Thus, the net effect of using biodiesel to displace conventional diesel is a reduction in the contribution of diesel engine exhaust to the greenhouse effect.

Engine Compatibility

Biodiesel can be produced in quantities that can supplement but not replace petroleum diesel. Therefore, most CI engines will continue to be designed to use petroleum diesel as their primary fuel. An important advantage of biodiesel is that it can function in these engines without modifications, and does not require engines especially designed to run on biodiesel.

When B100 is used as a fuel for CI engines, the following issues arise: solvent action, storability, cold filter plugging, elastomer compatibility, cetane number, heating value, and lubricating oil dilution (John Deere, 2001; Cummins, 2004).

Solvent action—Biodiesel has excellent solvent action. When spilled on paint, it can cause paint deterioration unless the spilled fuel is removed immediately. Biodiesel can also loosen deposits that have accumulated in the fuel tank and cause filter plugging until the tank, fuel lines, and filters are cleared of the deposits.

Storability—Because of its high level of unsaturation, biodiesel is susceptible to attack by oxygen from the air producing peroxides, acids, aldehydes, and viscosity-increasing polymers. Anti-oxidant additives should be used to control this process if the fuel must be stored longer than six months before use. Two additional issues arise with extended storage of biodiesel in the fuel tank. The fuel can bond with water, creating acids. Biodiesel is also a good

medium for microbial growth and such growth is accelerated by the presence of water. Both problems can be addressed by measures to keep water out of the fuel tank, for example, by keeping the tank full during idle periods to prevent humid air from condensing water on the tank inner walls.

Cold filter plugging—The molecular weight of biodiesel is approximately 30% higher than that of No. 2 diesel fuel. The larger molecules tend to precipitate out at higher temperatures than those of No. 2 diesel fuel, leading to problems of filter plugging in cold weather. Blending with petroleum diesel, especially No. 1 diesel, can help to alleviate this problem. Pour point depressant additives have also been found to be effective with biodiesel blends although their effectiveness with pure biodiesel is minimal (Shrestha et al., 2005).

Elastomer compatibility—Biodiesel can attack the elastomers found in some hoses and seals in the vehicle fuel system. Replacement of these hoses and seals with units made from Viton or other compatible materials that are impervious to biodiesel may be necessary.

Cetane number—Fuels with low cetane number can cause difficulty in initial starting of engines in cold weather. However, the cetane number of biodiesel is higher than that of most petroleum diesel.

Heating value—Biodiesel contains approximately 8% less energy per liter than petroleum diesel, leading to two performance issues. The peak power output of the engine is reduced proportionally with the reduction of fuel volumetric heating value and this becomes an issue on those occasions when maximum power is needed from the engine. The actual power loss may be somewhat less than 8% because biodiesel's higher viscosity reduces fuel system leakage and allows the fuel system to inject a greater volume of fuel. Regardless of the volume of fuel injected, the specific fuel consumption will be higher with biodiesel because of its lesser heating value. Both issues are reduced in severity when biodiesel is blended with petroleum diesel. For example, the heating value (weight basis) of B5 is only 0.6% less than that of petroleum diesel while, for B20, the heating value is only 2.5% less than that of petroleum diesel.

Lubricating oil dilution—Because biodiesel has larger molecules, its viscosity is 50% higher than that of No. 2 diesel. The higher viscosity leads to production of larger spray droplets in the combustion chamber, with a greater probability that some of the droplets can reach and impinge on the combustion chamber wall. Some of the impinging droplets can move past the rings to reach the crankcase, thus diluting the crankcase oil. When such dilution occurs, it may become necessary to reduce the interval between oil changes.

The above concerns arise when B100 is used as fuel for a CI engine but are diminished to the extent that the biodiesel is diluted with petroleum diesel. Cummins (2004) has made the following statement regarding the use of biodiesel: "Given the current industry understanding of biofuels and blending with quality diesel fuel, it would be expected that blending up to a 5% volume concentration should not cause serious problems." John Deere (2001) has made a statement that using biodiesel in concentrations

above 5% may lead to the following symptoms: power loss and deterioration of performance, fuel leakage through seals and hoses, corrosion of fuel injection equipment, coked/blocked fuel injector nozzles, filter plugging, lacquering/seizure of internal injection system components, sludge and sediments, and reduced service life. Both the Cummins and the John Deere statements are thus accepting of biodiesel in concentrations of 5% or less, but suggest problems that could potentially arise when biodiesel is used in concentrations greater than B5.

John Deere (2001) has stated that "Performance loss or failures related to the use of (biodiesel) are not considered the responsibility of John Deere. John Deere product warranty covers defects in workmanship and material as manufactured by John Deere." Cummins (2004) has made a similar statement regarding the use of biodiesel in their engines. Caterpillar has taken the same position regarding the use of biodiesel in their engines. The John Deere (2001) statement also notes that "Raw pressed vegetable oils are NOT acceptable for use for fuel in any concentration. In John Deere engines, these oils do not burn completely, and will cause engine failure by leaving deposits on injectors and in the combustion chamber." John Deere thus draws a sharp distinction between the use of raw vegetable oils and the use of biodiesel, i.e., the methyl esters of vegetable oils.

In a later statement (Nelson, 2002), John Deere specifically approved the use of up to 5% concentration of biodiesel fuel in their PowerTech diesel engines provided that the biodiesel meets the fuel specifications in ASTM PS 121-99, a provisional specification issued prior to ASTM D6751 or DIN 51606, the German standard.

In 2005, John Deere adopted an even more aggressive stance in favor of biodiesel (Nelson, 2005). They announced that John Deere diesel engines from all U.S. plants would be shipped with B2 in their fuel tanks by the end of 2005. Their spokesman announced that, "If B2 were used in all diesel engines in the U.S., the United States could displace the equivalent of about one billion gallons (3.8 billion liters) of foreign oil per year." Case IH has announced that B5 is approved in all of their engines and B20 is approved in engines without common rail fuel injection systems. Testing at higher blend levels is ongoing (Diesel Progress, 2006).

While cold flow limitations for biodiesel must be monitored, as for petroleum-based diesel fuel, operational problems for biodiesel have been few when the fuel meets the ASTM standard for biodiesel, ASTM D6751 (ASTM, 2002).

Current Status and Future Potential

Current Status and Extent of Acceptance

At the time of this writing, diesel prices are near all-time highs and as a consequence, interest in biodiesel could be characterized as a "gold rush." It is impossible to estimate the number of plants being considered by various groups. The NBB website listed 86 plants in 35 states operating as

of 13 September 2006. Total annual production capacity of these plants was stated to be 580.5 million gallons (2.2 billion liters). The website lists an additional 65 plants under construction and 13 plants undergoing expansion representing an additional 1.4 billion gallons (5.3 billion liters) of annual capacity. Actual production of biodiesel (NBB, 2006) has shown a sustained increase each year; NBB lists production as follows:

1999: 0.5 million gallons (1.9 million liters)
2000: 2 million gallons (7.6 million liters)
2001: 5 million gallons (18.9 million liters)
2002: 15 million gallons (56.7 million liters)
2003: 12 to 20 million gallons (45.4 to 75.6 million liters)
2004: 25 to 30 million gallons (94.5 to 113.4 million liters)
2005: 75 million gallons (280 million liters)
2006: Estimated over 500 million gallons (1.9 billion liters) of plant capacity, sales volume for 2006 has not yet been reported.

One key to biodiesel use is acceptance by engine manufacturers. In general, these manufacturers through their own warranty documents and through publications of the Engine Manufacturer's Association (EMA) have suggested a maximum of B5 as being acceptable, as noted earlier. The U.S. biodiesel industry in general has promoted B20 although there is considerable experience with B100 in Europe. A significant step in biodiesel use will be to obtain approval of EMA and their member companies on the use of biodiesel at higher blend levels.

Government Incentives

On-highway diesel fuel use is by far the largest market for biodiesel. With current incentives it is also the most price-competitive with diesel. According to the Energy Information Administration, the price breakdown for diesel at the pump is approximately 72% for the crude oil and refining, 7% for marketing and distribution, and 21% for taxes. The federal excise tax for on-highway fuel is 24.4 cents per gallon ($0.0645/liter). Each state adds an additional amount. In Idaho, for example, the state excise tax is another 25 cents per gallon ($0.0661/liter).

State and federal support for biodiesel has come about in many forms. Some states such as Minnesota and Washington have legislation mandating the use of biodiesel blends at 2% to 5%. Other states, such as Idaho and Illinois, have offered excise tax reductions. In some cases, governors, mayors, and others have required or encouraged fleets under their jurisdiction to use biodiesel where available. The Energy Policy Act of 1992 required fleets of 20 or more light-duty vehicles that were centrally fueled to convert to alternative-fueled vehicles. Amendments to the act provided that under prescribed conditions use of 450 gallons (1,701 liters) of biodiesel could be used to satisfy the requirement for one vehicle up to 50% of the total vehicle requirement (US DOE, 2006).

In 2001, the USDA established the Commodity Credit Corporation (CCC) Bioenergy Program. Under the program, the CCC makes payments to eligible bioenergy producers to encourage increased purchases of agricultural

commodities for the purpose of expanding production of bioenergy (ethanol and biodiesel) and to encourage the construction of new production capacity. The 2002 Farm Bill continued the program through Fiscal Year 2006, providing $150 million annually.

Bioenergy producers apply to the CCC to participate in this program. Payments are based on the increase in bioenergy production compared to the previous year's production. The program is structured to encourage participation by smaller producers. Producers with less than 65 million gallons (245 million liters) of annual production capacity are reimbursed on a ratio of one feedstock unit for every 2.5 feedstocks used, while larger facilities are reimbursed on a ratio of one to 3.5. Additionally, a payment limitation restricts the amount of funds any single producer may obtain annually under the program to 5% of the total funds available. Profitability is difficult in the first year of production for any company, and the margins in the first few years of production for new ethanol and biodiesel facilities are exceedingly tight. The CCC Bioenergy Program has provided valuable financial assistance to ensure the success of these new companies. This program expired in 2006.

Biodiesel VEETC Tax Credit

The American Jobs Creation Act of 2004 (JOBS Bill), signed into law in October of 2004, created the Volumetric Ethanol Excise Tax Credit (VEETC), which includes a tax credit for biodiesel. The Energy Policy Act of 2005 (H.R.6), extended the credit through 31 December 2008 and creates a similar tax credit for renewable diesel.

- The volumetric excise tax credit for *agri-biodiesel* is $1.00 per gallon ($0.26/liter). Agri-biodiesel is defined as diesel fuel made from virgin oils derived from agricultural commodities and animal fats.
- The volumetric excise tax credit for biodiesel from non-virgin oils is $0.50 per gallon ($0.13/liter). Biodiesel is defined as diesel fuel made from agricultural products and animal fats.

Small Biodiesel Producer Tax Credit

H.R. 6 also created a new credit for small agri-biodiesel producers equal to $0.10 per gallon ($0.026/liter) on the first 15 million gallons (56.7 million liters) of agri-biodiesel produced at facilities with annual capacity not exceeding 60 million gallons (227 million liters). Historically, small ethanol producers were allowed a similar credit. The tax credit is capped at $1.5 million per year per producer and, like the small ethanol producer, credit can be passed through to the farmer owners of a cooperative and the credit is allowed to be offset against the alternative minimum tax (AMT). The credit sunsets 31 December 2008 (RFA, 2006).

Potential for Displacement of Petroleum

While more than 46% of total U.S. energy consumption comes from oil and natural gas, only 4% comes from biomass, which is mostly wood (Energy Information Administration, 2006). More than 97% of U.S. transportation energy comes from petroleum, while biomass (primarily ethanol) contributes only 1.2%. Currently, the U.S. uses about 20 million barrels of petroleum per day (0.84 billion gallons/day, 3.2 billion liters/day), 25.5% of total world consumption. Net imports are about 56% of total consumption. For agriculturally produced renewable fuels, such as biodiesel, to make a significant contribution to this mammoth energy consumption will require every foreseeable agriculturally produced energy source that can be developed. Biodiesel from vegetable oils and animal fats is only one of these potential energy sources. Others, such as ethanol, are important components of the biomass complex.

Biodiesel can be thought of as the output from a solar collector that operates on CO_2 and water through the process of photosynthesis. The photosynthesis process captures the energy from sunlight to produce a hydrocarbon— vegetable oil. Carbon dioxide is used by the plant in the creation of the organic material and then the CO_2 is released in the combustion process when the fuel is used by a diesel engine. Photosynthesis is carried out by many different organisms, ranging from plants to bacteria. Energy for the process is provided by light, which is absorbed by pigments such as chlorophylls and carotenoids. Thus, through the process of photosynthesis, the energy of sunlight is converted to a liquid fuel that with some additional processing can be used to power a diesel engine. The photosynthesis process requires one major element: land. The crop must be planted over a wide area and to be economically feasible must compete advantageously with other crops that the landowner might choose to plant.

Of the more than 350 known oil-bearing crops, those with the greatest production potential in the U.S. are sunflower, safflower, soybean, cottonseed, rapeseed, canola, corn, and peanut oil. Modifying these oils to produce the methyl or ethyl esters has been shown to be essential for successful engine operation over the long term. Development of vegetable oil as an alternative fuel would make it possible to provide energy for agriculture from renewable sources located in the area close to where it could be used.

According to the 2002 Census of Agriculture (USDA, 2006a), harvested cropland in the U.S. consisted of 363.3 million acres (includes cropland used as pasture); an additional 71 million acres were idle (37 million), summer fallowed (16.5 million), or had crop failures (17 million). The distribution by individual crop is shown in Table 6. If one crop, rapeseed, were planted on every acre of the available harvested land at a production rate of 1 ton/acre (2,246 kg/hectare), which is equivalent to 100 gal/acre (934 liters/hectare) of oil and approximately 1,200 lb/acre (1,348 kg/hectare) of meal, 36.3 billion gallons (137 billion liters) of oil would be produced. Another 3.7 billion gallons (14.0 billion liters) could be produced on the idle land. In 2002, 72.4 million acres of U.S. cropland, 16.7% of all cropland, was planted to soybeans. The average yield for soybeans is 38 bushels per acre with an oil content of 1.4 gallons per bushel (5.3 liters/bushel) or 53.2 gallons per acre (497 liters/hectare). Thus, if all land were planted to soybeans the U.S. could produce 23 billion gallons (87 billion liters) of methyl or ethyl alcohol required in the transesterification

Table 6. Major crops and harvested acres for 2002 (2.471 acres = 1 hectare). Source: 2002 Census of Agriculture.

Crop	acres	Crop	acres
Barley	4,015,654	Tobacco	428,631
Corn	74,914,518	Field and grass seed	1,422,133
Oats	1,996,916	Forage crops	64,041,337
Popcorn	309,879	Dry edible beans	1,691,775
Millet	282,664	Dry edible peas	281,871
Rice	3,197,641	Lentils	198,997
Rye	285,366	Potatoes	1,266,087
Sorghum	7,161,357	Sweet potatoes	92,310
Wheat	45,519,976	Hops	29,309
Canola	1,208,251	Mint	108,798
Flaxseed	641,288	Pineapple	10,211
Peanuts	1,223,093	Berries	206,034
Safflower	182,292	Vegetables	3,433,269
Soybeans	72,399,844	Orchards	5,330,439
Sunflower for oil	1,500,828	Pasture	60,557,805
Sunflower, non-oil	332,607	Failed crops	17,069,564
Cotton	12,456,162	Summer fallow	16,559,229
Sugarbeets	1,365,769	Idle land	37,281,096
Sugarcane	978,393	Total harvested cropland	363,300,000

process (10% to 15% on a volume basis of the vegetable oil produced.) This estimate of maximum vegetable oil production is equivalent to 1.04 times the current annual consumption of petroleum diesel used for on-highway transportation if rapeseed were the feedstock and 0.60 times if soybean oil were used.

Computations of the land that could realistically be used for vegetable oil production are complicated. Certainly land must be available for domestic food production. It is logical to assume that some production of food for export will continue to be needed. It is also reasonable that crop rotations will require that only a portion of the land could be in vegetable oil production in any one year. In 2002, 37 million acres (14.9 million hectares) of cropland were reported as idle. This idle cropland could produce 3.7 billion gallons (14.0 billion liters) of vegetable oil per year or 10% of the diesel used in transportation. In an earlier report, the author made an estimate of additional cropland potentially available for vegetable oil production by comparing crop production for several of the major crops with domestic use (Peterson et al., 1995). Any production over domestic use was termed excess and, using the national average production for that crop, an estimate of excess crop production land of 62 million acres (25.1 million hectares) was calculated. This land could produce an additional 6.2 billion gallons (23.4 billion liters) of vegetable oil or an additional 16% of our on-highway diesel fuel consumption at the expense of foreign exports of the commodities currently produced on that land.

A discussion of the potential production of biodiesel will consider four questions: (1) how much petroleum diesel do we use, (2) how much fat and oil do we currently produce,

(3) how are these fats and oils currently used, and (4) how much used oil is available for biodiesel production?

(1) How much petroleum diesel do we use? As shown in Table 7 (Energy Information Administration, 2006) for the year 2005, total use of oil and kerosene in the U.S. amounted to 63.2 billion gallons (238.7 billion liters). The largest share of this is 38.1 billion gallons (143.8 billion liters) for on-highway diesel fuel.

(2) How much fat and oil do we currently produce? The U.S. produces about 3.15 billion gallons (11.9 billion liters) of vegetable oil (Table 8). Of this, 77% comes from soybeans, 10% from corn, 4% from cottonseed, 9% from

Table 7. Annual sales of diesel fuel, 2005, U.S. only (Energy Information Administration, 2006).

	Annual sales of diesel fuel	
	(billion gallons)	(billion liters)
On-highway diesel	38.1	143.8
Residential heating	6.15	23.2
Commercial	3.22	12.2
Industrial	2.46	9.3
Oil company	0.47	1.8
Farm	3.22	12.2
Electric power	0.91	3.4
Railroad	3.45	13.0
Vessel bunkering	2.01	7.6
Military	0.27	1.0
Off-highway	2.96	11.2
Total fuel oil and kerosene	63.2	238.7

Table 8. Total annual production of oils and fats in the U.S. (Pearl, 2002).

	Vegetable Oil Production	
	(billion gallons)	(billion liters)
Soybean	2.44	9.22
Peanuts	0.29	1.10
Sunflower	0.13	0.49
Cottonseed	0.13	0.49
Corn	0.32	1.21
Others	0.09	0.34
Total vegetable oil	3.15	11.9
	Animal Fats	
	(billion gallons)	(billion liters)
Inedible tallow	0.51	1.93
Lard and grease	0.17	0.64
Yellow grease	0.35	1.32
Poultry fat	0.30	1.13
Edible tallow	0.21	0.79
Total animal fats	1.55	5.86

peanuts, and 4% from sunflower (Pearl, 2002). The U.S. imported 3,630 million pounds (0.48 billion gallons; 1.8 billion liters) and exported 6,040 million pounds (0.79 billion gallons; 3.0 billion liters) of edible fats and oils. Current vegetable oil production is approximately equivalent to the on-farm use of diesel fuel and about 10% of on-highway diesel use. An estimate of the annual production of rendered fats and greases is also given in Table 8. This shows that the total amount of animal fats is approximately 50% of the amount of vegetable oil so the earlier estimates could be increased by 50% if this resource were available. Since animal fats are a by-product of the meat production industry, it would not be expected that increased demand and higher prices for biodiesel feedstocks could have much impact on total animal fat supply.

(3) How are these fats and oils currently used? For the 1999-2000 record-keeping year, 6,450 million pounds (2,932 million kg) were used for baking or frying fats, 1,727 million pounds (785 million kg) for margarine, 8,939 million pounds (4,063 million kg) for salad or cooking oil, and 436 million pounds (198 million kg) for other edible uses totaling 17,551 million pounds (2.3 billion gallons; 8.7 billion liters) for edible food products. In the year 2000, the U.S. also used 1,896 million pounds (862 million kg) for industrial fatty acid production, 3,253 million pounds (1,479 million kg) for animal feeds, 366 million pounds (166 million kg) for soap production, 100 million pounds (45.4 million kg) for paint and varnish, 138 million pounds (62.7 million kg) for resin and plastics, 120 million pounds (54.5 million kg) for lubricants and similar oils, and 471 million pounds (214 million kg) for other industrial uses. This industrial use totals 6,344 million pounds (0.834 billion gallons; 3.15 billion liters).

According to the USDA Economic Research Service (ERS, 2006), recent end-of-year stocks of soybean oil vary from 1.7 to 3.0 billion lbs (227 to 400 million gallons; 858 to 1,512 million liters) and exports are 1.1 to 1.3 billion lbs (146 to 173 million gallons; 552 to 654 million liters). The sum of these two (373 to 573 million gallons; 1,410 to 2,166 million liters) might be considered to be an approximation to the amount of vegetable oil readily available for biodiesel use. Increases beyond this level will require diversion of oil from existing food and industrial uses or increases in the amount of domestic crush, which will likely depress soybean meal markets, lessening the incentive for increasing soybean production.

(4) How much used oil is available for biodiesel production? Estimates of potential production often ignore "double counting." It should be recognized that all used oils started out as new oil so the production figures must be reduced by any used oil use. For example, yellow grease was originally produced as vegetable oil or animal fat. We should not include both in our estimates.

Pearl (2002) estimated that 0.35 billion gallons (1.32 billion liters) of yellow grease and 1.2 billion gallons (4.5 billion liters) per year of other animal fats are collected in the U.S. each year. Yellow grease is primarily used oil from fast food restaurants, delis, and similar sources.

Personnel at the National Renewable Energy Laboratory (NREL) (Willtsee, 1998) estimated that about 9 pounds/person/year (1.16 gallons/person/year; 4.38 liters/person/year) of used oil and 13 pounds/person/year (1.69 gallons/person/year; 6.39 liters/person/year) of trap greases and similar oils are produced each year. U.S. population estimated by the Census Bureau was 300,500,000 at the end of 2006 (U.S. Census Bureau, 2006). Using the estimates of NREL, this would suggest 0.35 billion gallons (1.32 billion liters) of used oil per year and 0.51 billion gallons (1.93 billion liters) of trap greases.

The Jacobsen Fats and Oils bulletin lists 40 companies dealing in yellow grease. The collecting and recycling of used oils is a highly competitive business. An analysis of one of these companies reported that the most competitive part of their business was obtaining the product. Yellow grease goes into the manufacture of soap, textiles, cleansing creams, inks, glues, solvents, clothing, paint thinner, rubber, lubricants, and detergents, to list a few. Its principle use is as a livestock feed additive. It makes the feed less dusty and adds lubrication to the feed, reducing wear on milling machinery. It is a dense source of energy, which is important for animals like cattle and horses that have a hard time eating more than they already do.

It is likely that many of the current uses of used oil will continue to take precedence for a major portion of these oils. Mad cow disease has reduced the use of some rendered oil products for animal feed opening an opportunity for more to be used as biodiesel feedstock. If 25% to 30% of used oil were available for biodiesel, this would be about 100 million gallons per year (378 million liters). The use of trap greases for biodiesel may add to that total but they will require further development before becoming widely used because of the potential for contamination with chemicals,

pesticides, sewage components and water, and their high free fatty acid content.

World Vegetable Oil Production

The production of vegetable oil in the entire world is estimated at 34 billion gallons (128 billion liters) as shown in Table 9. The world production of vegetable oil is equivalent to 89% of the U.S. on-highway diesel fuel use or 54% of the total U.S. fuel oil and kerosene use in a year. It would require more than the entire world production of these vegetable oils to replace the U.S. on-highway diesel fuel use.

Table 9. World vegetable oil production.
Source: USDA (2006b); conversion from metric tons
to gallons and liters by the authors.

Oil	2005/2006 (metric tons)	2005/2006 (billion gallons)	2005/2006 (billion liters)
Soybean	33.8	9.90	37.4
Palm	35.4	10.26	38.8
Rapeseed	16.8	4.94	18.7
Sunflower	10.1	2.95	11.2
Peanut	5.2	1.51	5.71
Cottonseed	4.6	1.34	5.07
Palm kernel	4.3	1.26	4.76
Coconut	3.5	1.04	3.93
Olive	2.3	0.67	2.53
Total	116.0	33.87	128.0

Potential Production of Biodiesel

It would be very ambitious to produce the amount of diesel used on the farm about 3.2 billion gallons (12.1 billion liters). That would require all of the vegetable oil currently produced in the U.S. and would require about 15% of our total production land area.

The authors expect that a challenge for biodiesel production will occur at about 0.2 to 0.5 billion gallons (0.8 to 1.9 billion liters) when the increased demand for oil causes price increases and acquisition of additional feedstocks will become very difficult in years when production of oilseeds is low due to weather or market conditions.

The other side of this argument is that a 0.2 to 0.5 billion gallon (0.8 to 1.9 billion liters) biodiesel industry would have a significant beneficial impact on agriculture and rural communities. It would provide an outlet for surplus vegetable oil crops and land currently being used to produce surplus crops could be switched to oilseeds to provide additional feedstock for biodiesel.

In the future, there is considerable potential for increased vegetable oil production, worldwide. Palm oil production is already expanding with Indonesia increasing palm production acreage by 40% (ERS, 2006). This increased area may require 3 to 5 years to reach production, and there is significant resistance to the environmental impact. However, it is clear that with time vegetable oil production can be substantially increased. Tropical countries have the greatest near-term potential but even arid-climate plants such as *Jatropha curcas* are becoming important oil sources in India and Africa.

The complete replacement of petroleum fuels with vegetable oil-based fuels is not possible in the near term. However, the combination of energy conservation with the development and adaptation of new, higher-yielding, oil-bearing crops could eliminate a substantial portion of the world's dependence on petroleum.

Improving Production Potential

Additional acreage, improved varieties, diversion of exports, and use of idle cropland could all increase total vegetable oil production. Each of these methods for improving production has specific challenges to overcome. For additional acreage of fats and oils, the price must be competitive with the displaced crop. Improved varieties require time and money for research. Idle cropland must be made available for crop production. This idle land is generally low in productive capacity, is often highly erodable, and is land that is potentially lower yielding.

University of Idaho plant scientists have developed yellow mustard varieties that have the potential to significantly reduce the cost of the oil used in biodiesel production. This reduced-cost oil is made possible by producing cultivars with specific properties remaining in the meal after the oil is removed. One of the potential uses for the meal is as a soil fumigant to replace chemicals currently in use today, such as methyl bromide, which will soon be removed from the market due to its toxicity.

Biodiesel has the potential to be a very large agriculturally produced commodity. However, biodiesel is unlikely to displace a significant portion of our petroleum diesel in the near future because of the limited capacity we have to produce vegetable oil and because there are more important food uses for the major portion of our edible fats and oils.

Conclusions

Biodiesel is a viable substitute for petroleum-based diesel fuel. Its advantages are improved lubricity, higher cetane number, cleaner emissions (except for NO_x), reduced global warming, and enhanced rural development. Its cold flow properties and oxidative stability merit attention but problems have been shown to be manageable by conventional means, such as blending and additives.

Vegetable oil has potential as an alternative energy source. However, vegetable oil alone will not solve our dependence on foreign oil within any practical time frame. Use of this and other alternative energy sources could contribute to a more stable supply of energy. Major production centers on the level of modern petroleum refineries have not been developed. However, the number of plants is expanding rapidly and many additional ones are under study.

The economics of biodiesel fuels compared to traditional petroleum resources are marginal; public policy needs to be revised to encourage development. State and federal governments have made strides in that direction but much more

will be required if vegetable oils are to achieve their potential. Increased vegetable oil production would require a significant commitment of resources. Land for production would need to be contracted, crushing and biodiesel production plants need to be built, distribution and storage facilities constructed, and monitoring of users for detection of problems in large-scale use are all needed to encourage development of the industry.

In addition to the oil produced, a vegetable oil crop such as winter rape also produces considerable biomass. It has been estimated that a 2,000 lb/acre (2,246 kg/hectare) crop of winter rape produces 100 gal/acre (934 liter/hectare) of oil, 1,250 lb/acre (1,404 kg/hectare) of meal and 5,000 lb/acre (5,616 kg/hectare) of biomass normally left on the field at harvest. It was estimated that the energy equivalent of these by-products is 350 gal/acre (3,269 liter/hectare) of diesel fuel, which is equivalent to 8.33 bbl/acre (20.6 bbl/hectare). The meal can also be used as a high-protein livestock feed. However, if there were a major shift of land into production of vegetable oil crops for energy these by-products could likely be used for direct combustion or for production of ethanol. Removal of all biomass would have implications for maintenance of soil fertility that are not included in this calculation. Utilization of the entire crop leads to the concept of a complete "energy" crop. Agricultural policy makers need to seriously consider means to encourage the development of these energy crops.

The magnitude of our energy needs provides an inexhaustible market for our total agricultural production capacity at the highest possible level. We could put the farm back to work providing for our food needs and also growing crops and livestock for energy. Energy is the only crop that could never grow in surplus.

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